THE UNIVERSITY of EDINBURGH

IRIS FIRE

IMPROVING THE RESILIENCE OF INFORMAL SETTLEMENTS TO FIRE

UNIVERSITEIT STELLENBOSCH UNIVERSITY

Fire Spread in Communities

with an informal settlement focus

Burgers Program and Combustion Institute Summer School on Fire Safety Science

Wed June 7th 2023

By David Rush

University of Edinburgh

1. https://www.groundup.org.za/article/photos-fire-destroys-numerous-homes-hout-bay/
2. https://www.thesouthafrican.com/read-the-truly-heart-wrenching-stats-from-cape-towns-latest-township-fire/

EPSRC
Engineering and Physical Sciences Research Council

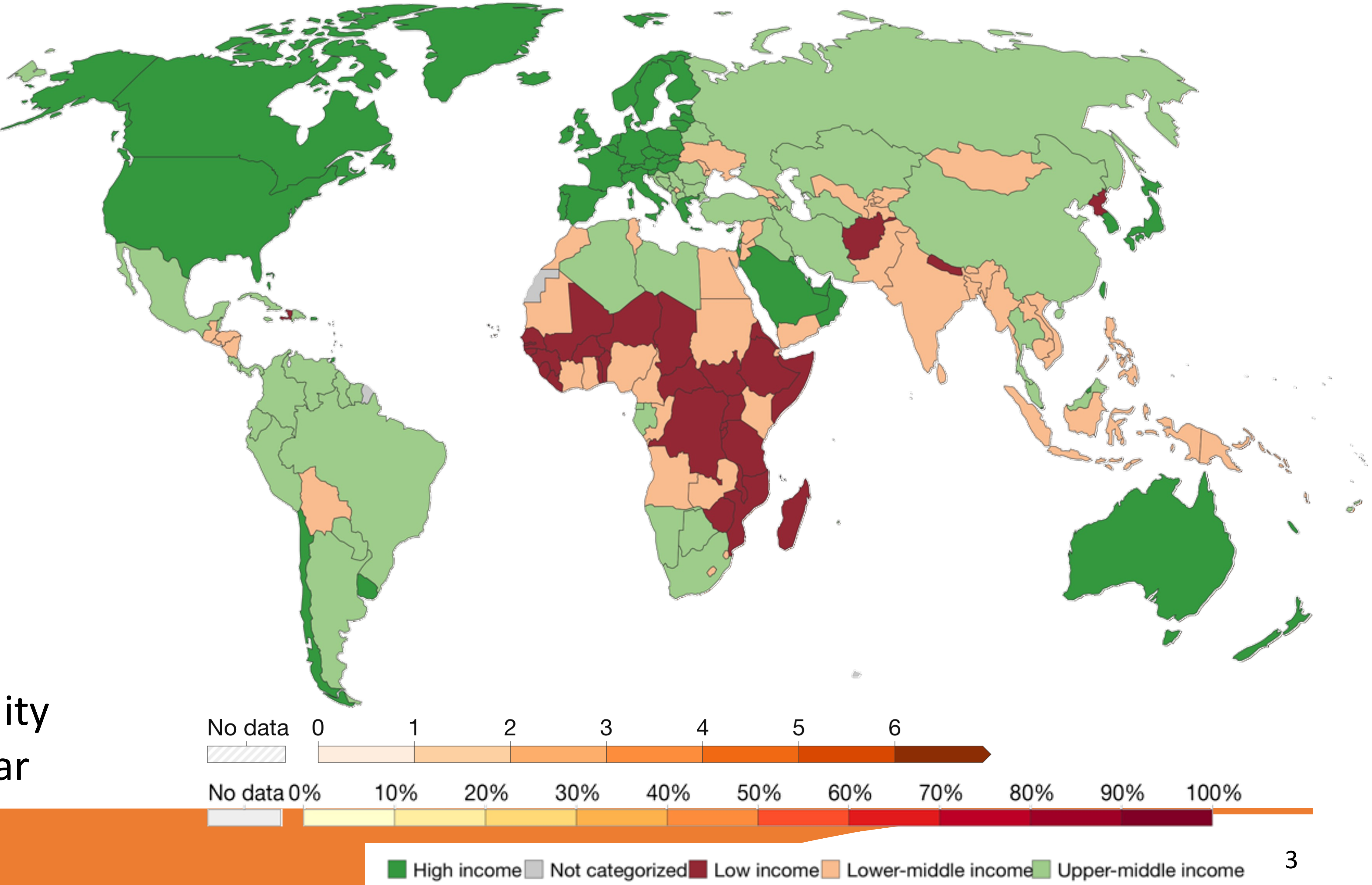
E·S·R·C ECONOMIC & SOCIAL RESEARCH COUNCIL
Economic and Social Research Council
Shaping Society

Learning outcomes

- Fire spread in communities – dynamic situation
  - To effectively manage fire and people - need to understand and model how fires spread – good fire models.
- Learning outcomes of this lecture
  1. Scales and context of the problem.
  2. How fires spread IN communities (not TO as that is WUI).
  3. How we are currently modelling fire spread and fire spread risk.
  4. What the complexities are that we are still researching (assume everything)
- Lecture – taster menu rather than banquet meal

Consequences of fire

- Deaths
  - **115,000 – 180,000 ppl/yr**
  - **90-95% in LMICs**
  - UK – 0.38/100,000/yr
  - Singapore – 0.19
  - Lesotho – 7.75
  - HIC – 0.69 (US – 0.82)
  - UMIC – 1.13
  - LMIC – 1.87
  - LIC – 3.08
  - SSA – 3.34
- Disability
  - A leading cause of morbidity
  - 8-10M DALYs lost each year

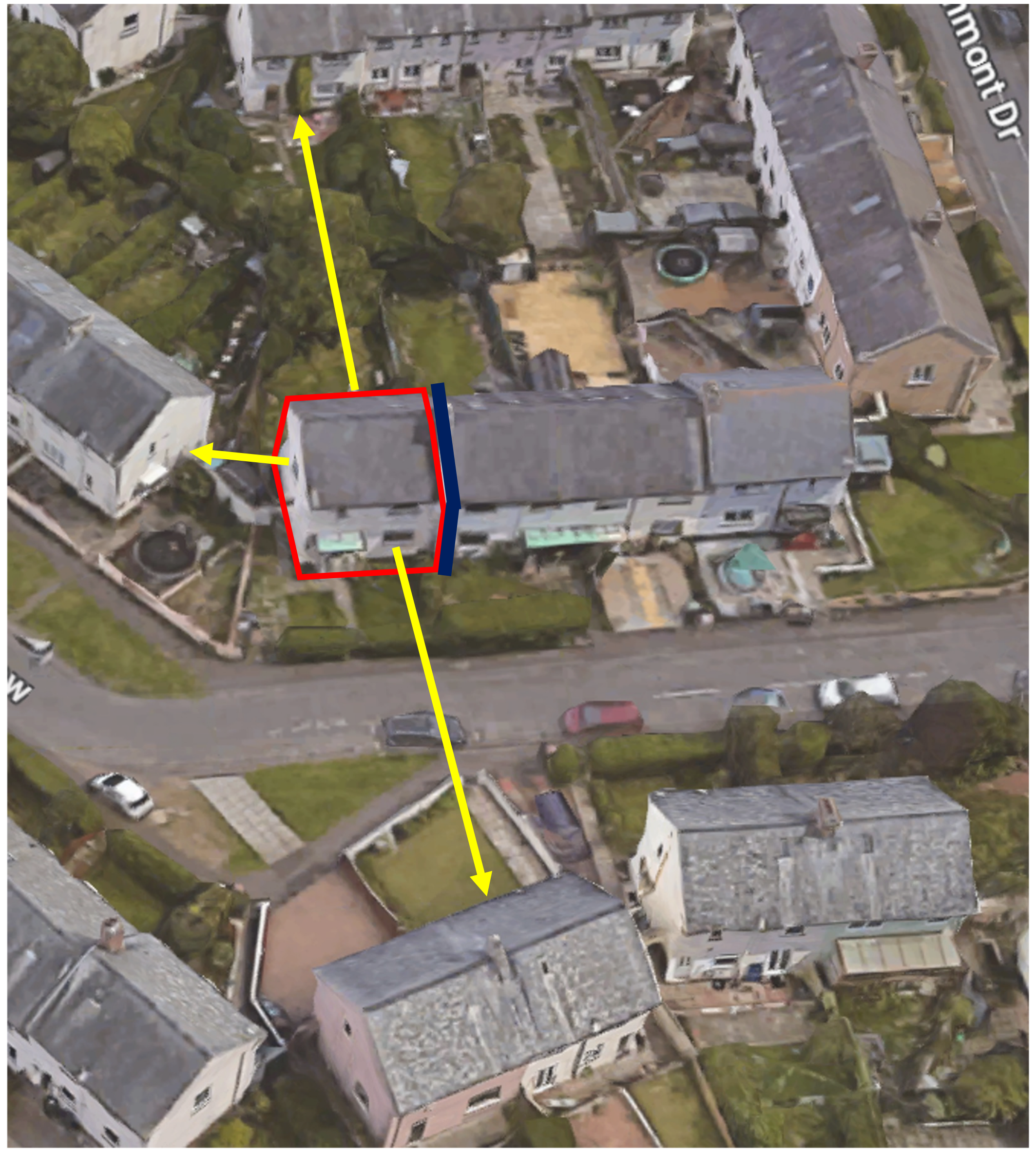


All maps from ourworldindata.org

Scale of Urban Fire Spread – UK

- Limited/Rare
  - Regulation
  - Historic settlements
- So when?
  - Failure of regulations
  - Other significant event as initiator
  - e.g., Wildfire, EQ, Volcano

Red – Home
Blue – Party wall – Solid construction – no fire through
Yellow – distance to neighbouring homes



https://wildfiretoday.com/wp-content/uploads/2022/07/A-wildland-urban-interface-fire-destroyed-structures-in-the-UK-July-19-2022.-Sky-News-3.jpg

Scale of Urban Fire Spread – Global South

2011 – Bahay Toro – Philippines
10,000 homeless, 1 dead (5yr old), 5 hrs

March 2017 – Imizamo Yethu – South Africa
2,100 homes – 9,700 homeless, 4 dead, 13.5 hrs

April 2014 – Valparaiso – Chile
2,500 homes – 12,500 evacuated, 15 dead (4 days)

January 2018 – Kijiji – Kenya
6,000 homeless, 5 dead, 8hrs (lack of water)

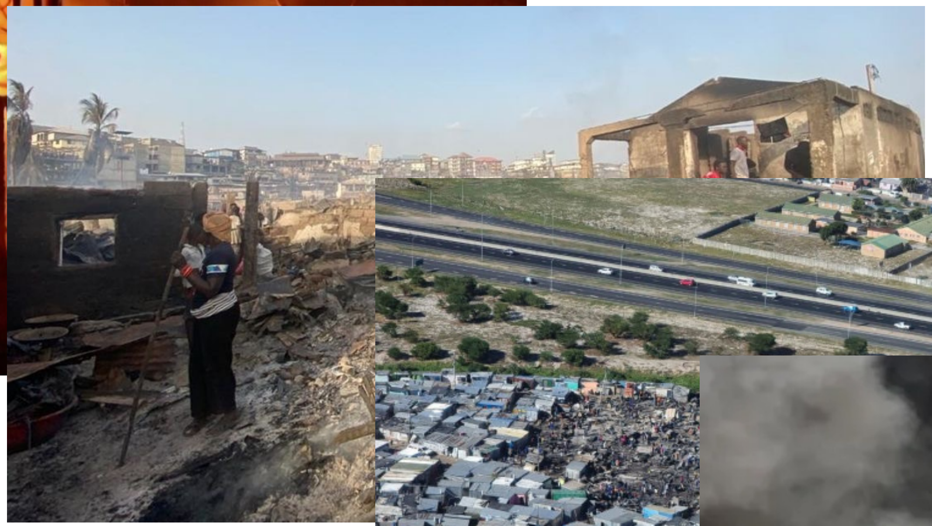
5. https://www.rtbf.be/info/monde/detail_manille-un-mort-dix-mille-sans-abri-apres-un-incendie-dans-un-bidonville?id=5618523
6. https://www.news.com.au/world/lose-homes-in-philippines-slum-fire-in-manila/news-story/8971233f01a574b2d967239b703d9d94
7. https://www.theatlantic.com/photo/2014/04/fire-destroys-2000-houses-in-valparaiso/100716/
8. https://www.theatlantic.com/photo/2014/04/fire-destroys-2000-houses-in-valparaiso/100716/

5. https://www.groundup.org.za/article/photos-fire-destroys-numerous-homes-hout-bay/
6. https://www.thesouthafrican.com/read-the-truly-heart-wrenching-stats-from-cape-towns-latest-township-fire/
7. https://www.kenyans.co.ke/news/26646-only-structure-mysteriously-remained-intact-after-langata-fire
8. https://globalresilience.northeastern.edu/2018/02/five-killed-and-thousands-displaced-after-fire-rips-through-kijiji-slum-in-nairobi/

Scale of Urban Fire Spread – Global South (2)

Dhaka, Bangladesh, 2019
1000+ structures (15,000 ppl)

Moria, Greece, 2020
13,000+ homeless



Freetown, Sierra Leone, 2021
8000 homeless, 400 injured

Joe Slovo, Cape Town SA, 2022
1000+ homeless

Cox's Bazar, Bangladesh, 2023
12000+ homeless

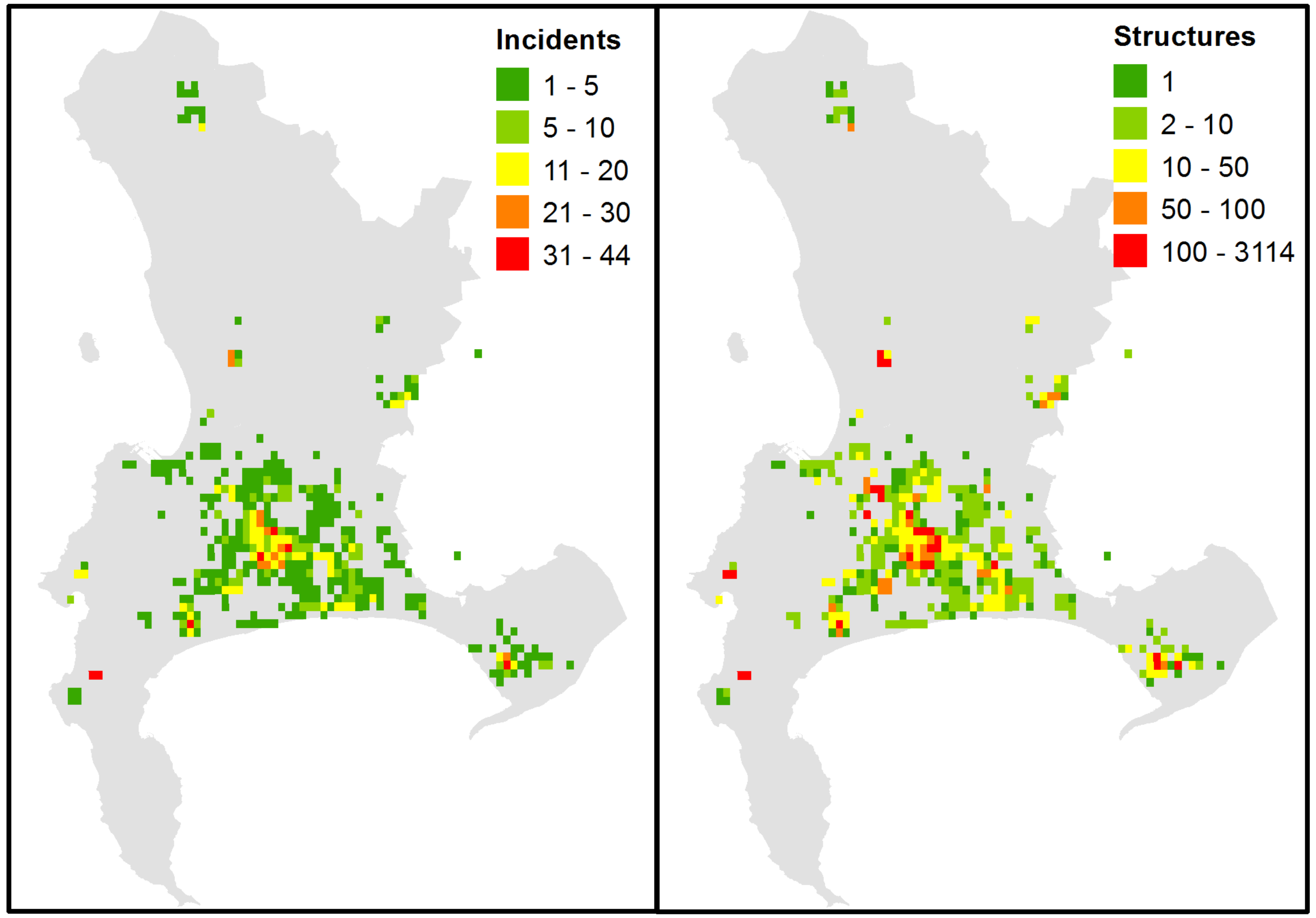
Guryong Village, Seoul, South Korea, 2023
Hundreds homeless
900 fire fighters
5 helicopters - 5HRs

https://www.bbc.com/news/world-asia-49382682
https://www.bbc.com/news/world-europe-54082201
https://www.bbc.com/news/world-asia-64343167
https://www.bbc.com/news/world-asia-56504561
https://ewn.co.za/2022/04/17/hundreds-homeless-after-fire-rips-through-joe-slovo-informal-settlement
https://www.humanity-inclusion.org.uk/en/news/a-devastating-fire-in-freetown-leaves-thousands-homeless-and-in-shock

Frequency & severity – Cape Town, South Africa

35% informal settlements – 4.3M people

- Anecdotally – at least one fire a day in IS in Cape Town
  - 2/3 affect one dwelling
  - **1/3 affect more than one**
    - Can be into the thousands
    - **Once a week a fire will affect more than 20 dwellings**
- Initial ignition causes vary
  - Cooking, electrical faults/surges, arson, children playing with fire etc…



What is an informal settlement?

- Slum, shanty town, favela, refugee camps etc.
- For our purposes: *an area of self-built homes of poor quality materials with a lack of adequate services and sanitation*
- UN estimates 1 bn already live in informal settlements, expected to reach 1.2 bn by 2050
  - 90% of the growth in Africa and SE Asia

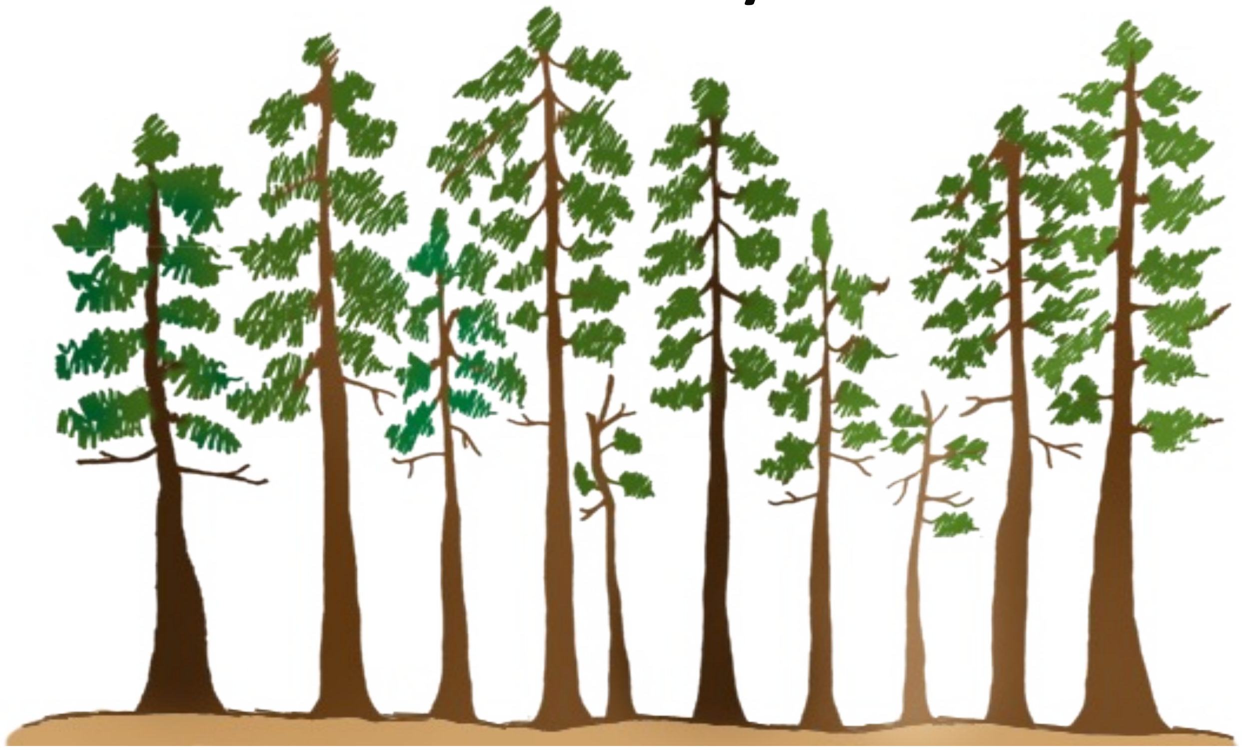
Fires exacerbated by access…

Jahangirpuri slum
New Delhi
4th June 23
Photo: Deep Nair

Kijiji slum
Nairobi
17th May 23
Photo: Faith Kipyegon

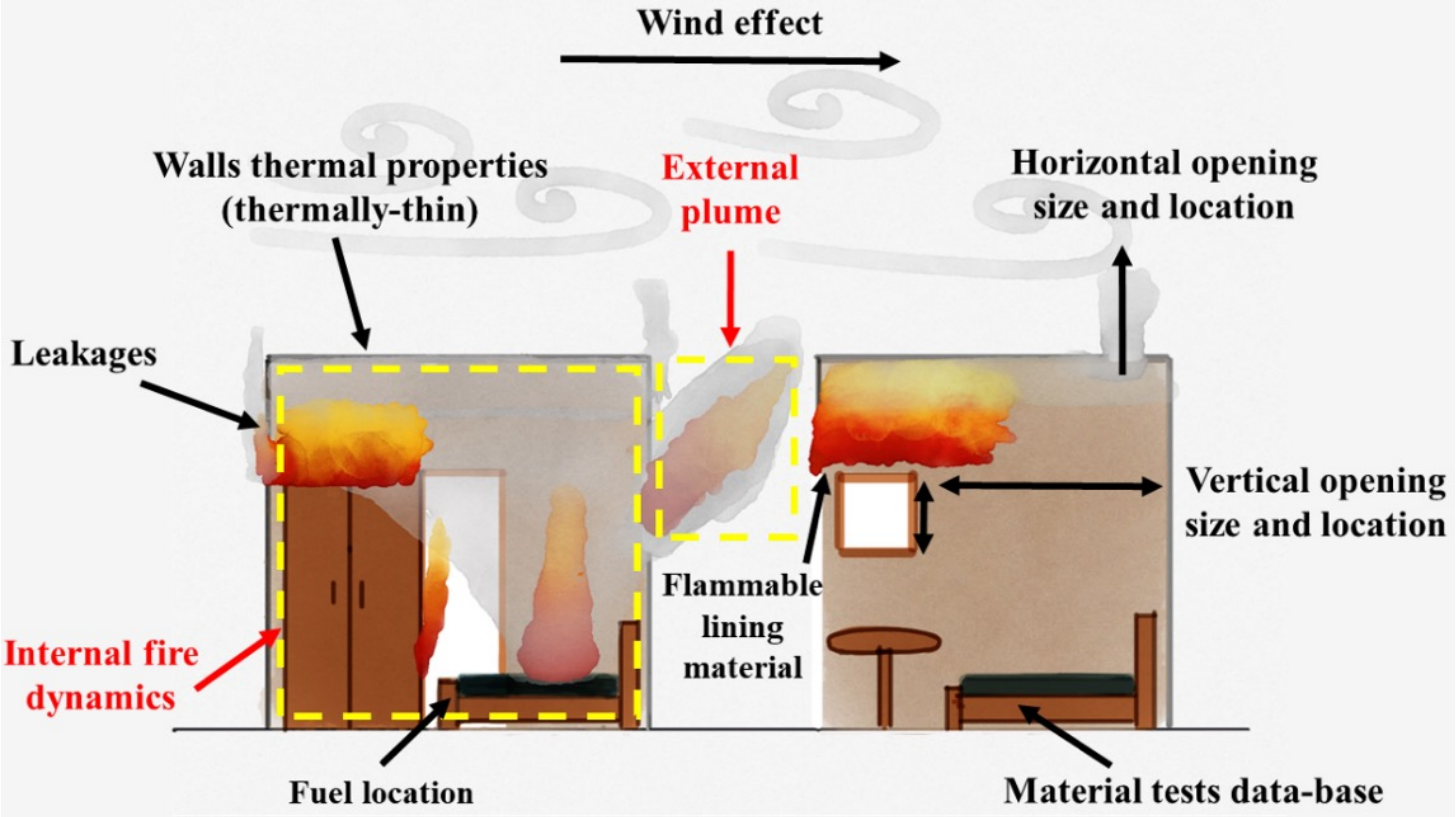
How fires spread IN communities (not TO as that is WUI).

- Urban fires are as much a set of social phenomena as it is physical.
  - Physics is the same around the world
  - People, and their reactions, differ even within the same community.
- WUI vs community fires



What this lecture will be all about

(and what we still don't fully know)



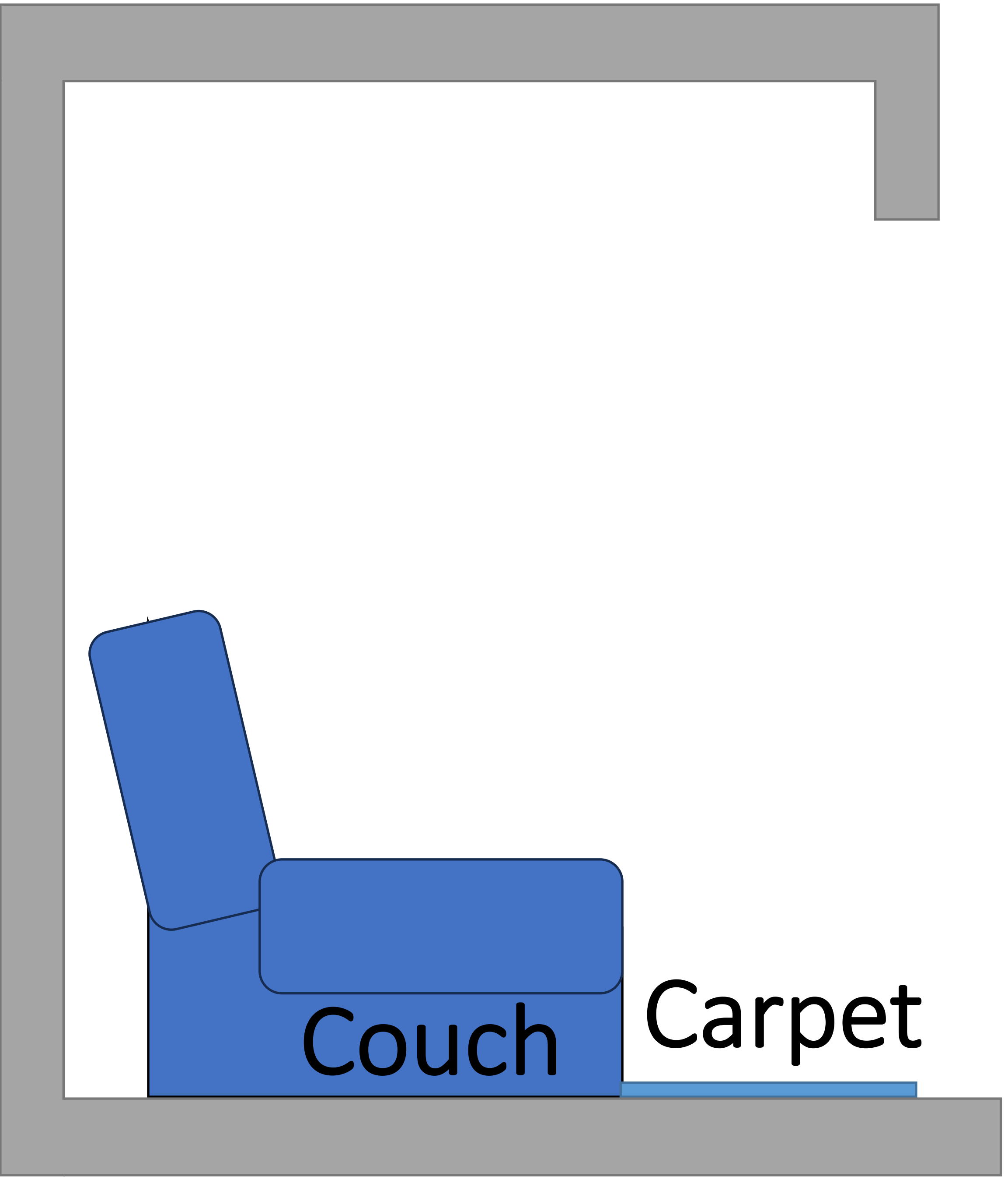
What happens in the box …

DOESN'T stay in the box

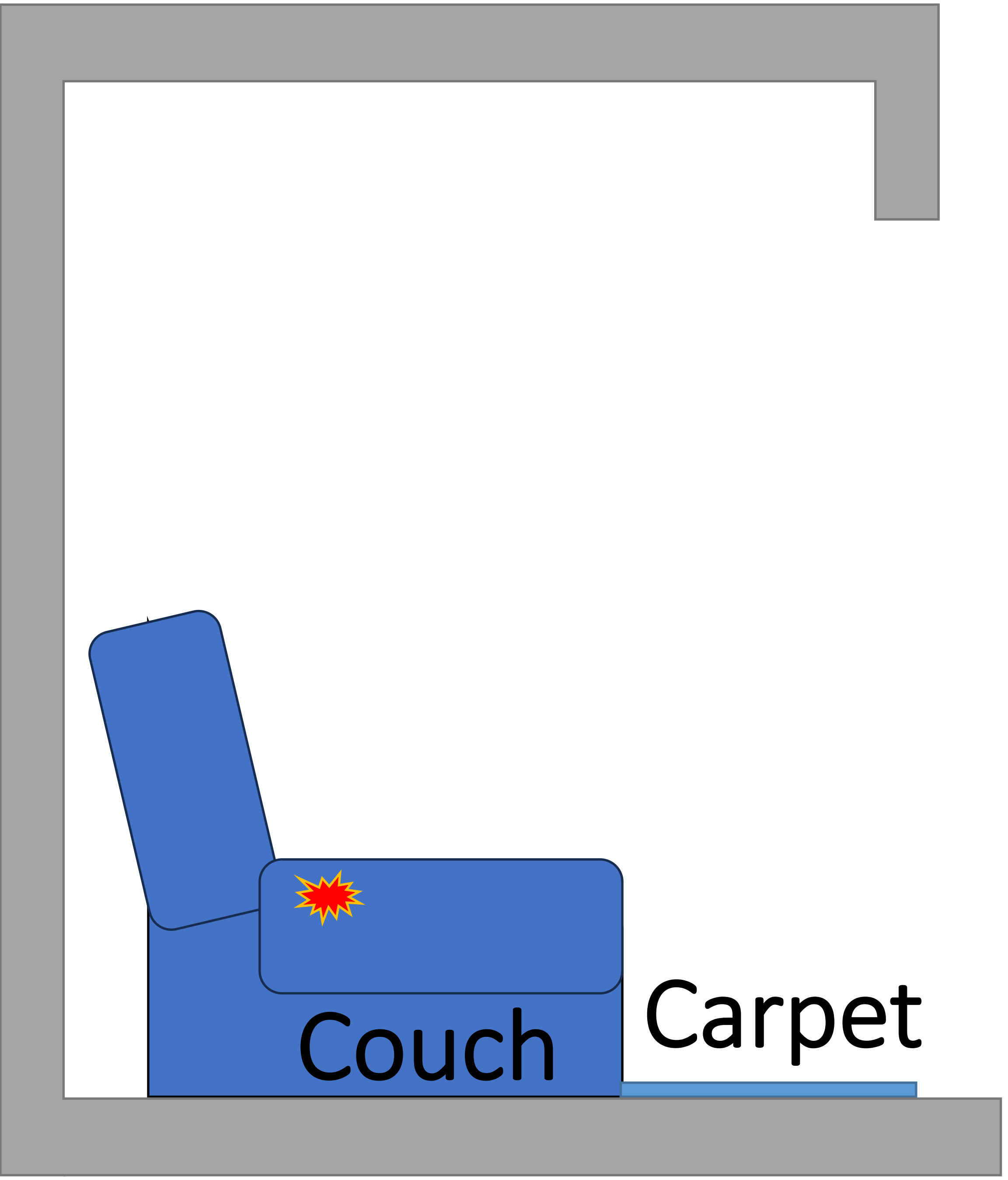
Urban fire spread driven by **compartment fire dynamics**

[1] Beshir M. Experimental and Numerical Study for the Principal *Fire Dynamics within Thermally-Thin Bounded Compartments (Case study: Informal Settlements in Cape Town, South Africa).* Unvierstiy of Edinburgh, 2022.

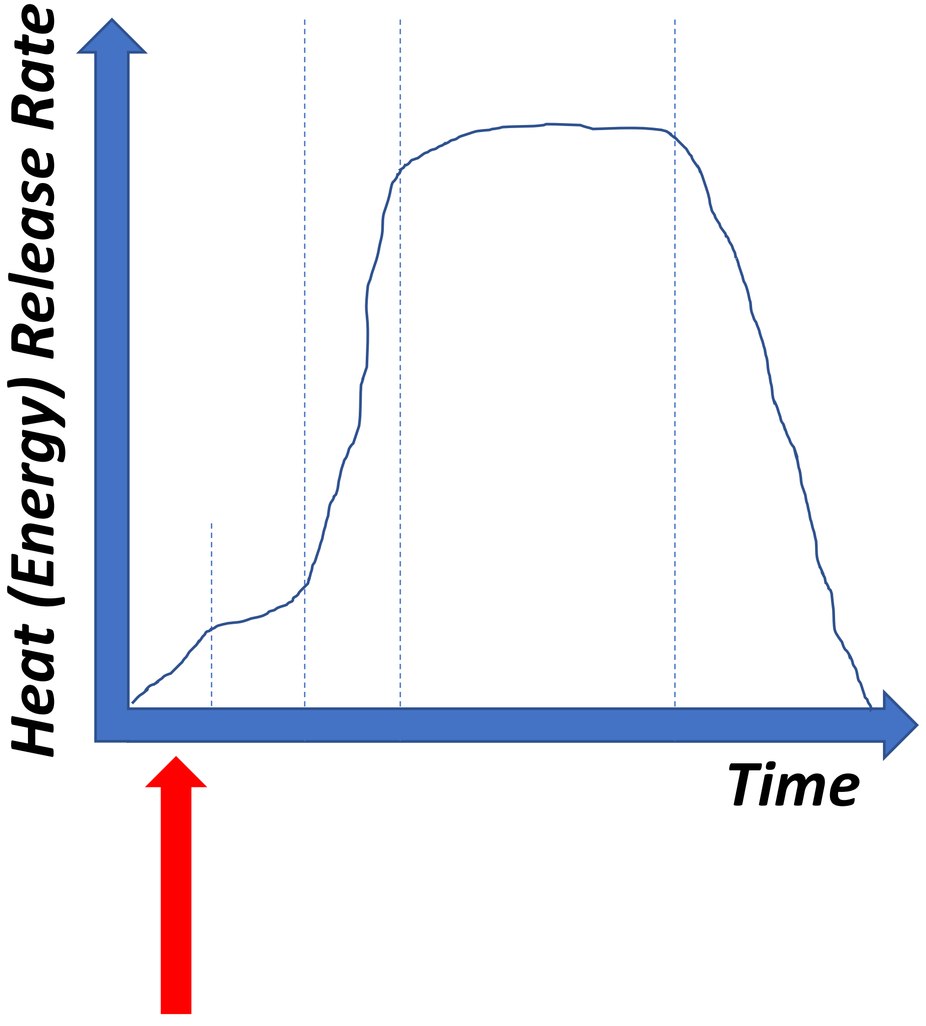
Compartment fire dynamics



Ignition source
Temperature ~ 20 °C

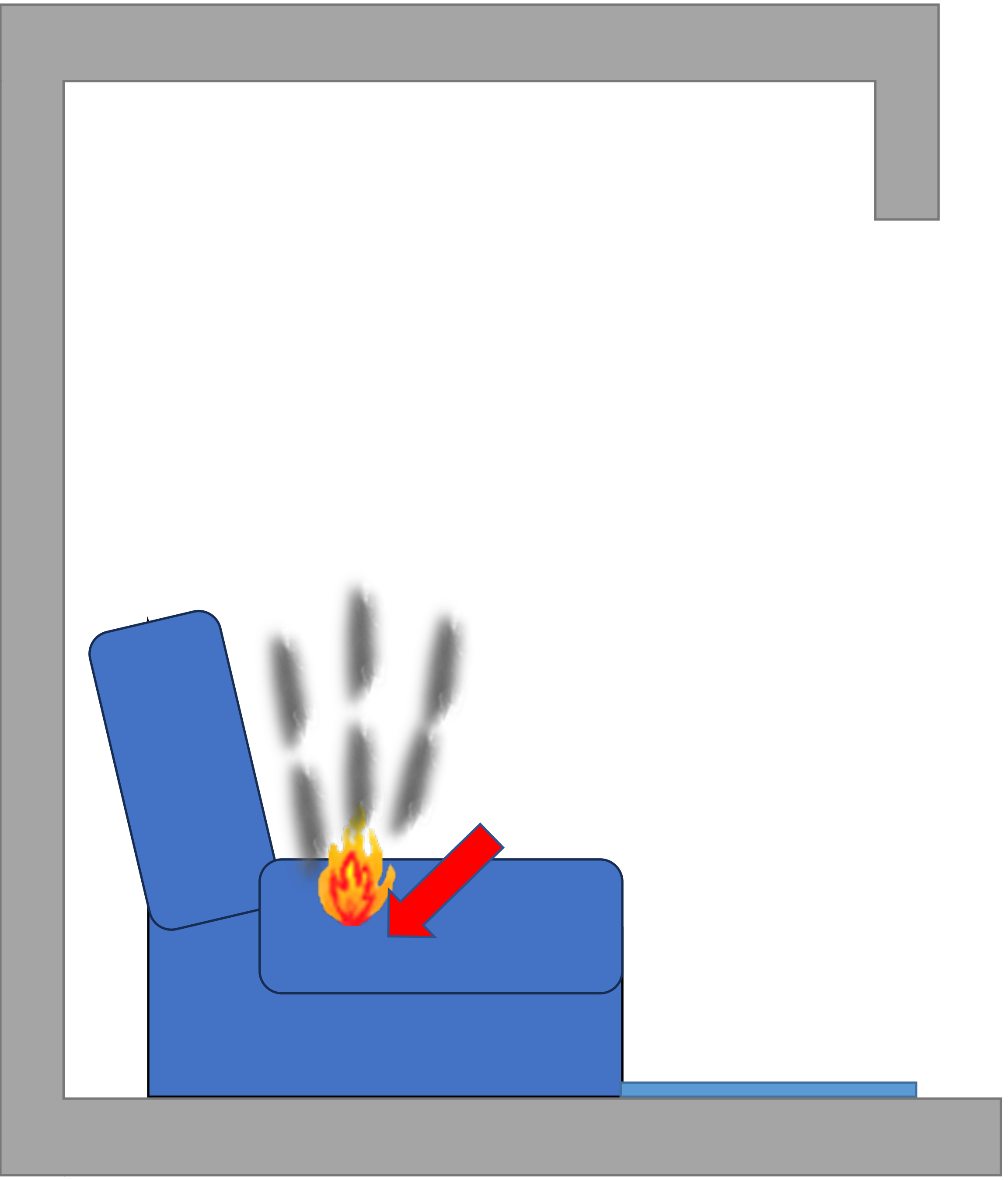


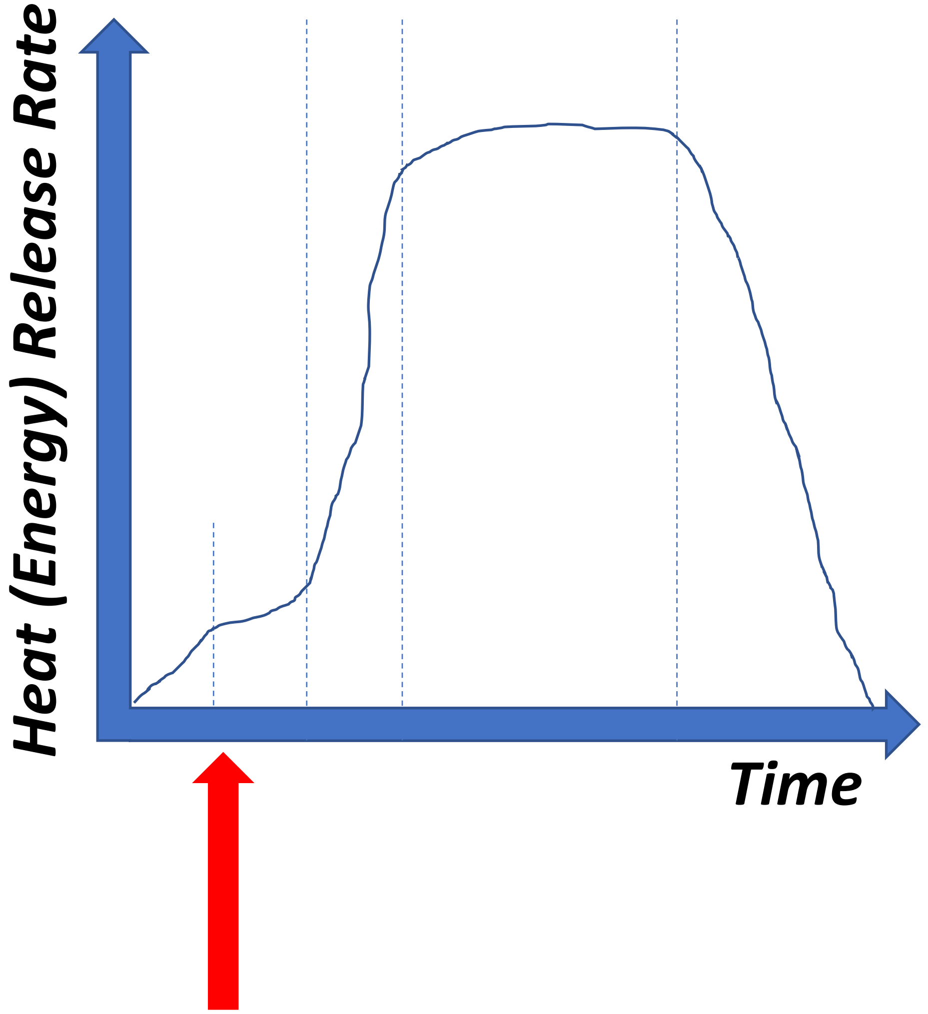
Pre-Flashover



Incipient

Ignition started
Temperature ~ 30 °C

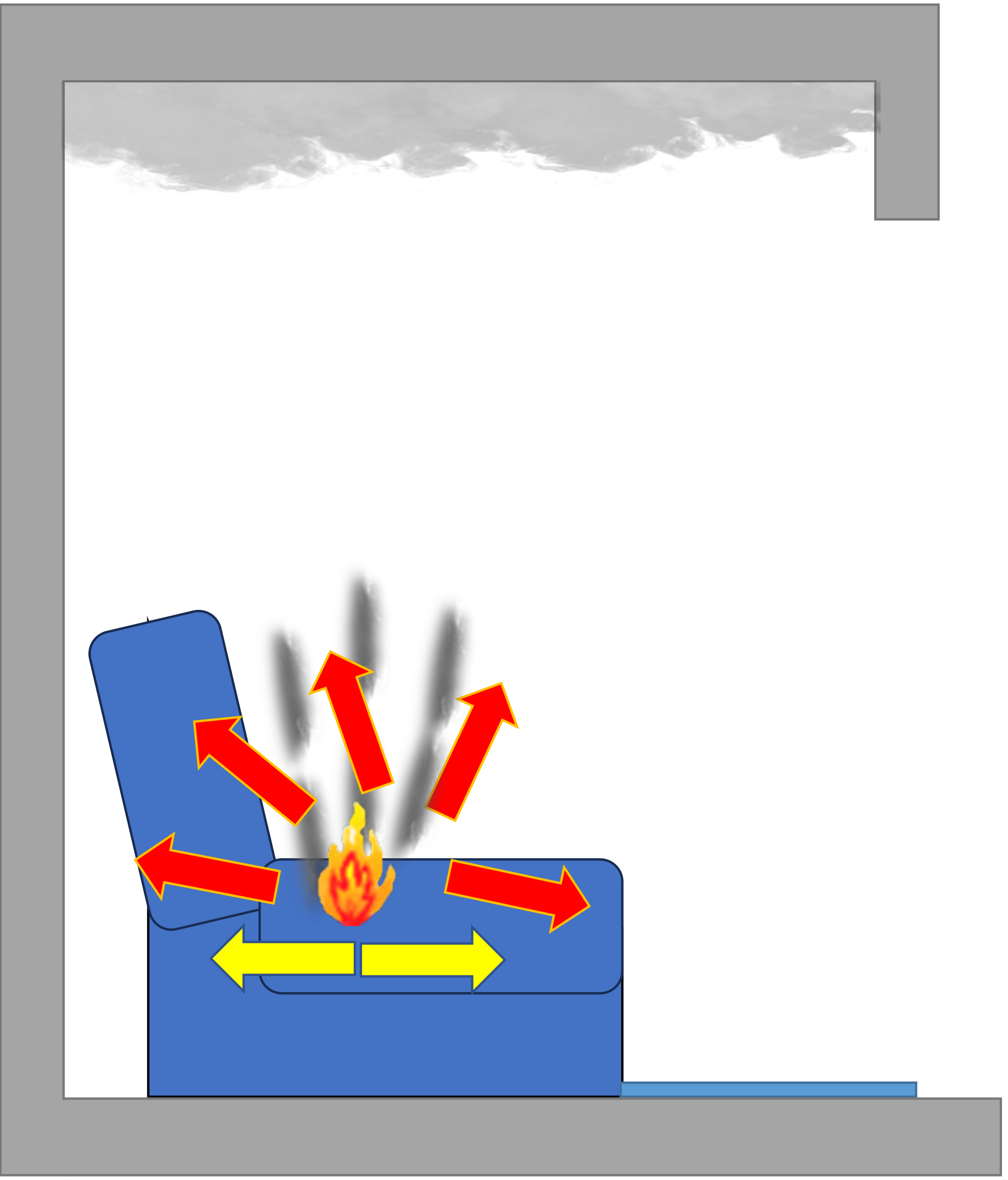




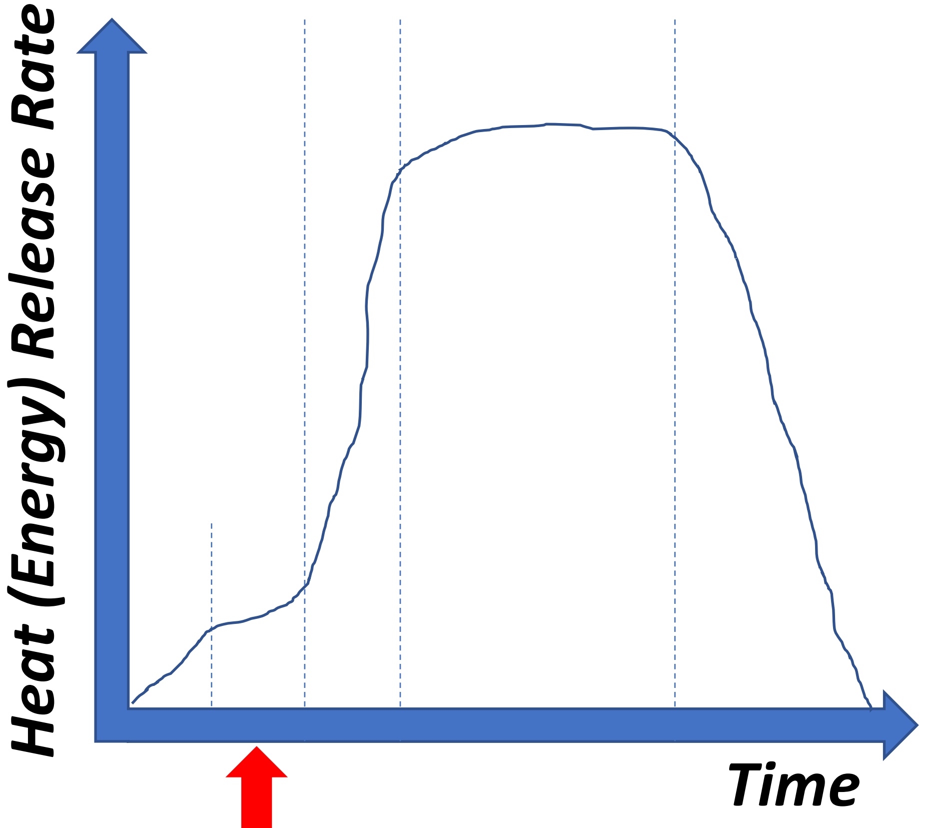
Growth

Pre-Flashover

Heat Transfer:
'Radiation'
'Conduction'

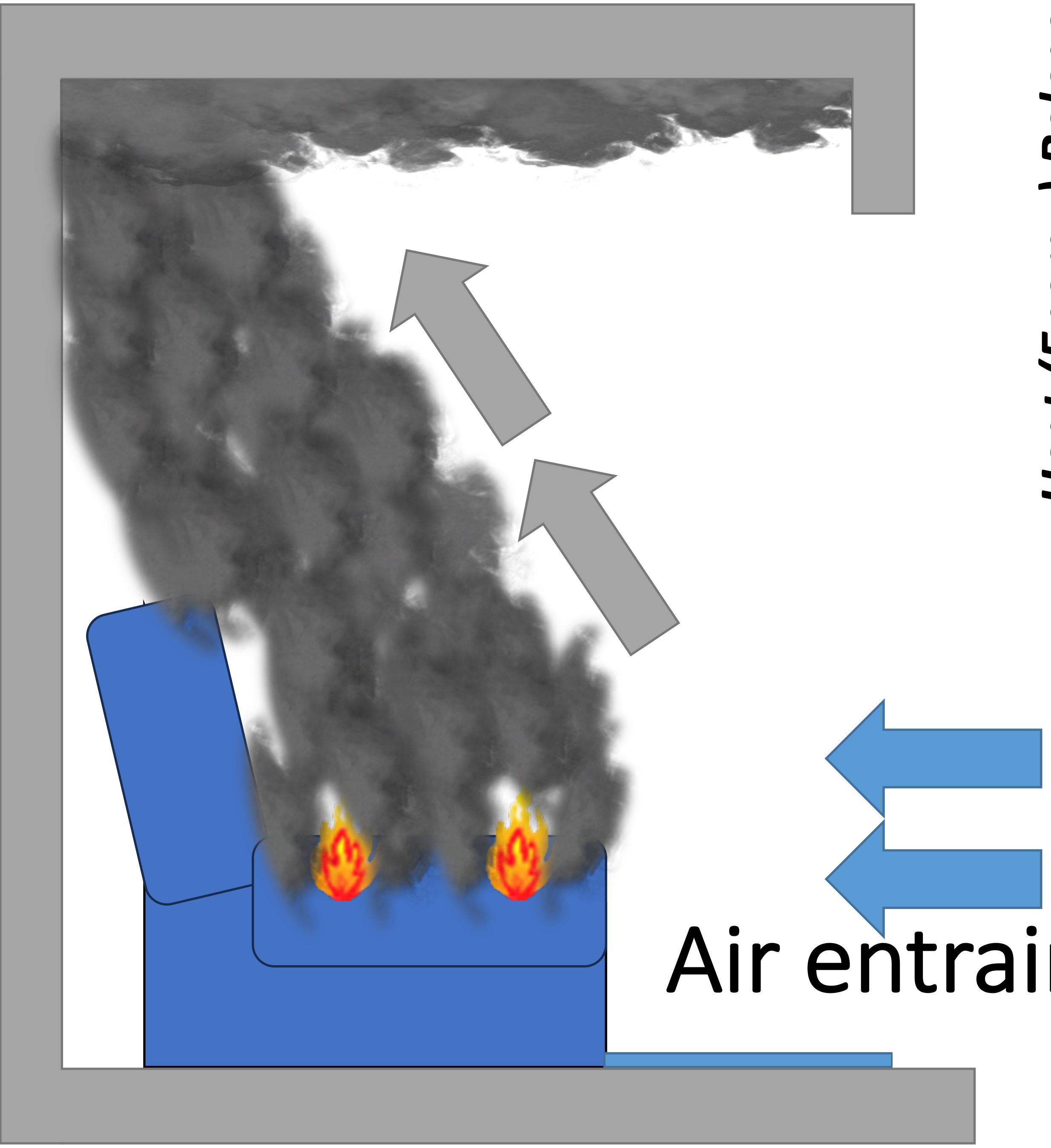


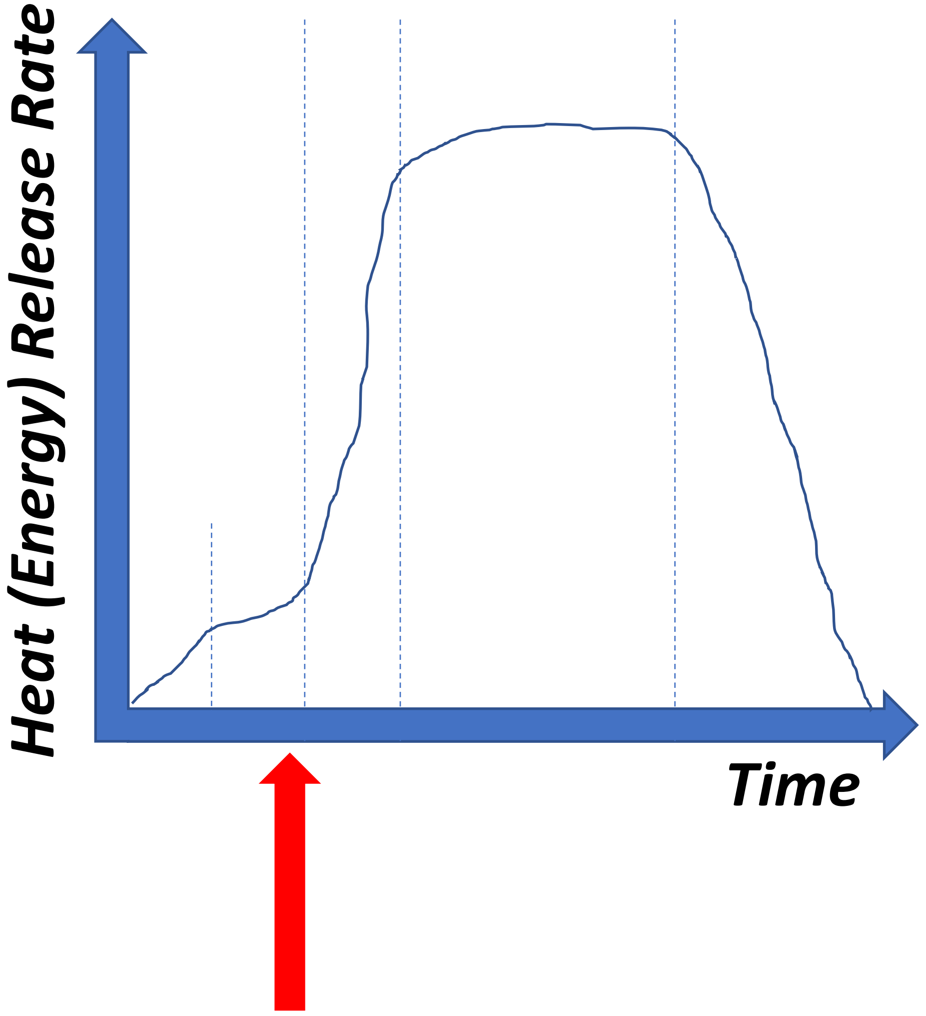
Pre-Flashover



Growth

Flame spread
and flow dynamics
Temperature ~ 200 °C



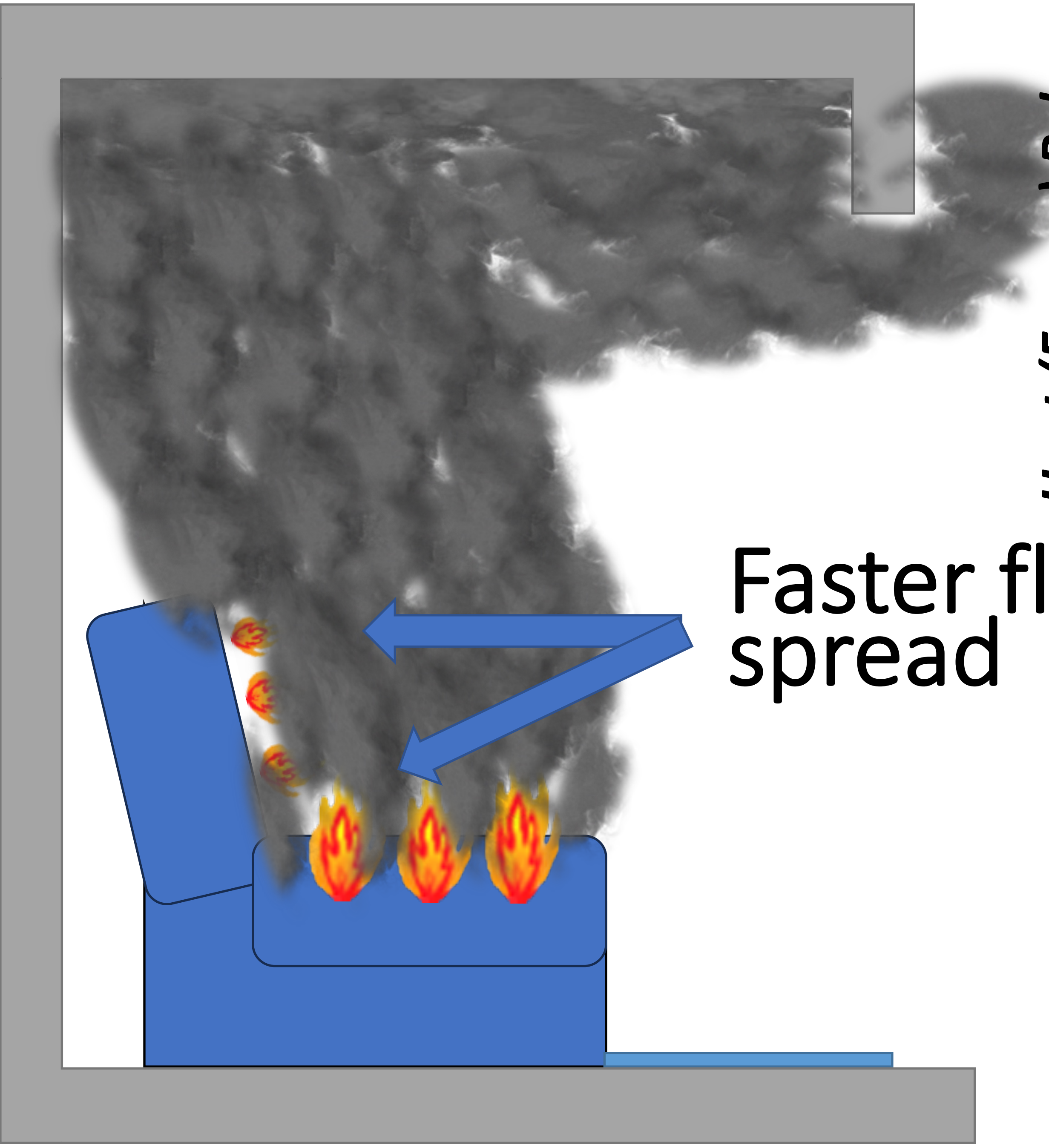


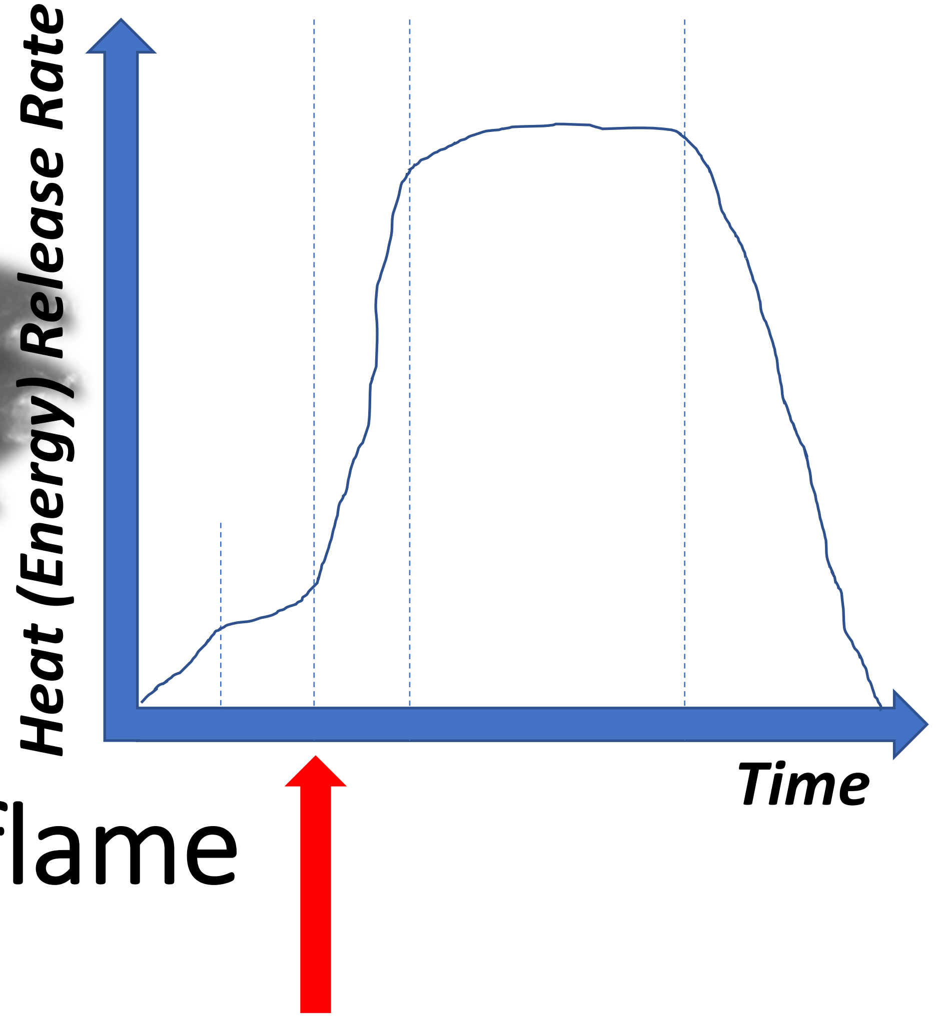
Growth

Air entrainment flow

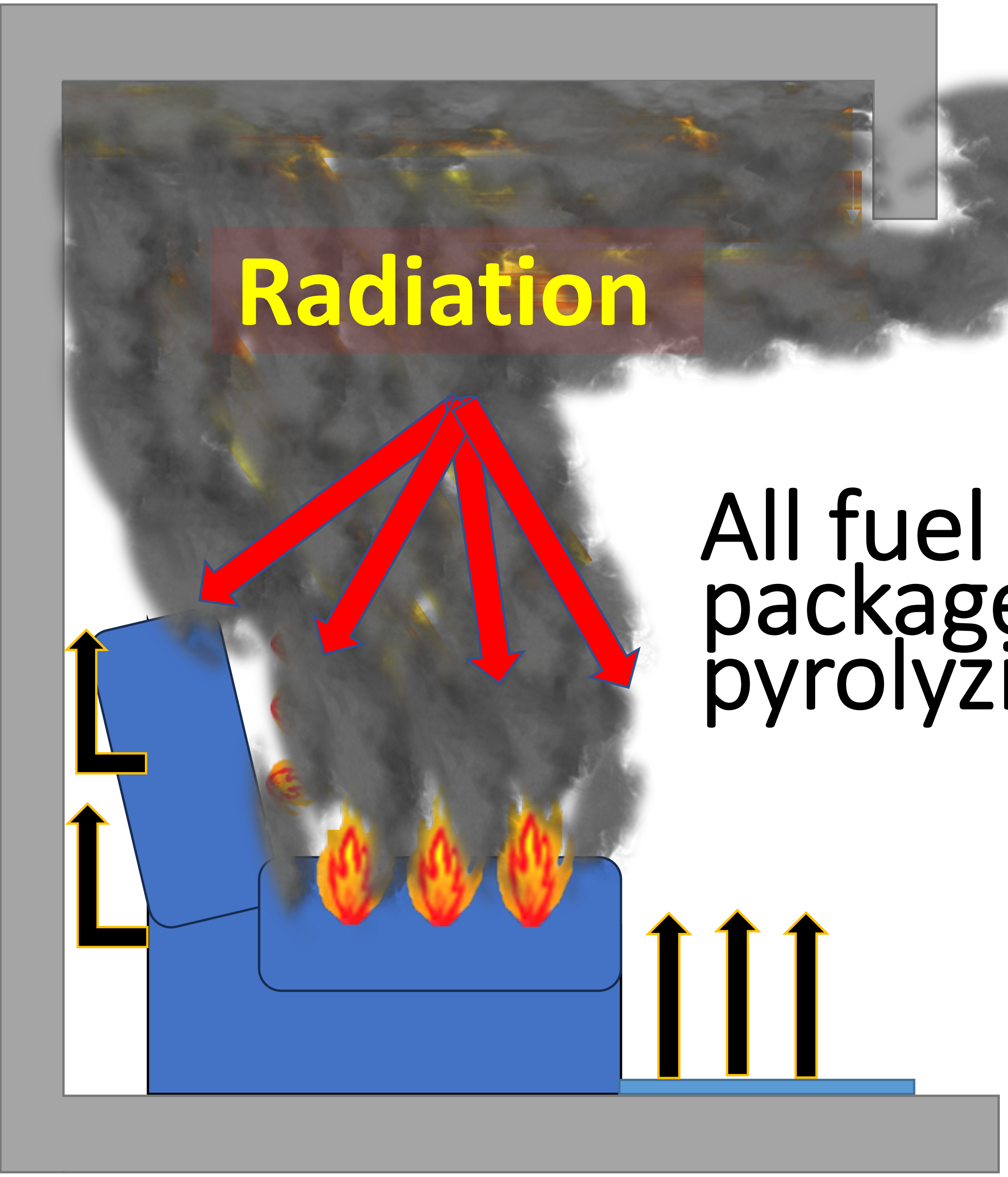
Pre-Flashover

Smoke layer building up
Temperature ~ 400 °C



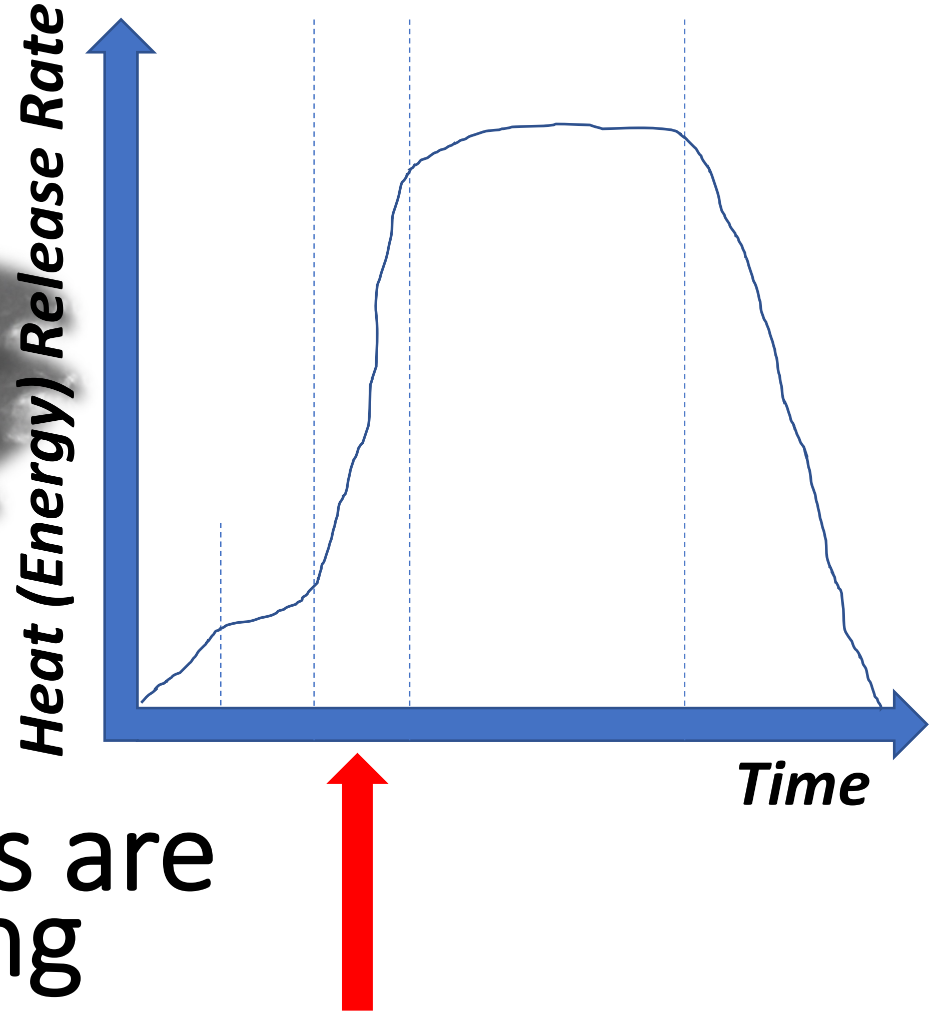


Smoke ignites
Temperature ~ 800 °C



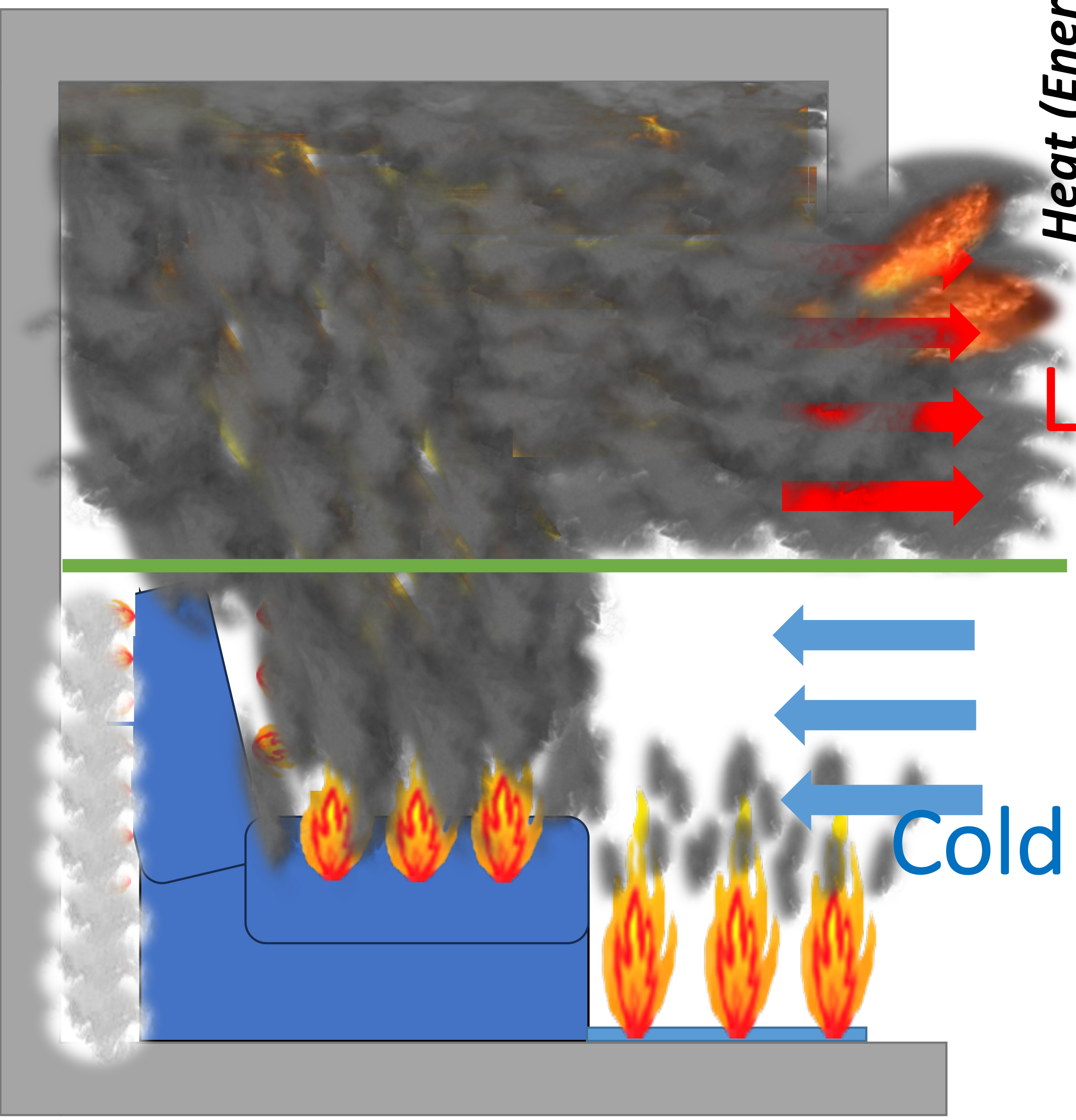
Flashover

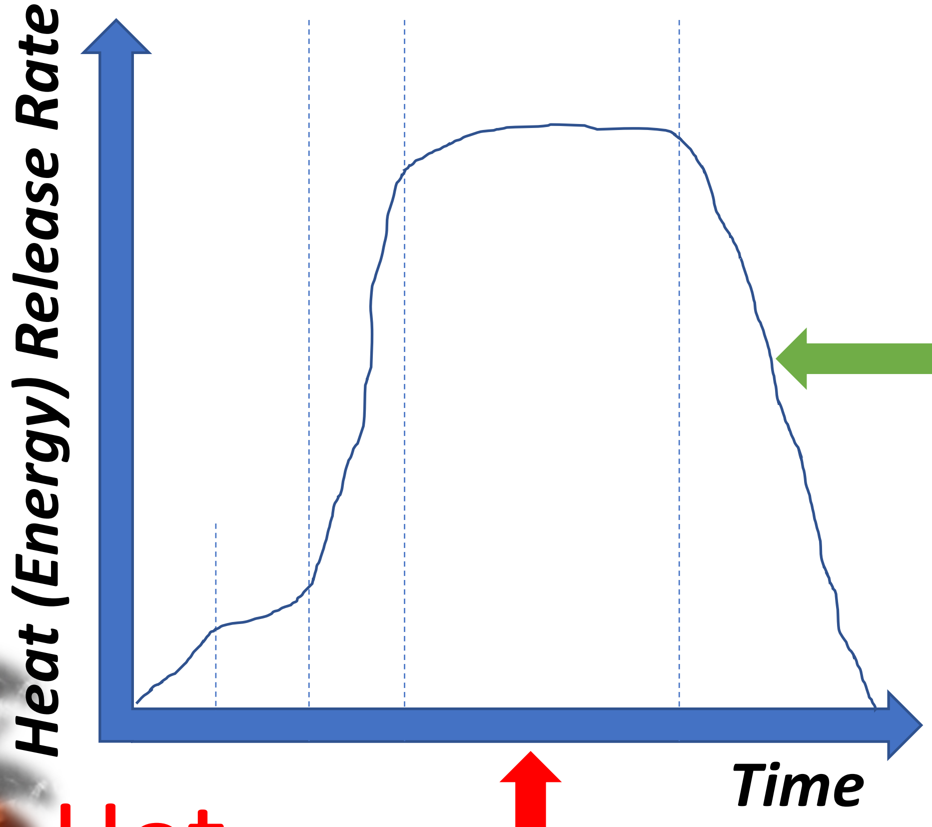
All fuel packages are pyrolyzing



Flashover

All items caught fire
Temperature ~ 1200 °C





Decay

Hot Layer

Fully-developed

Cold Layer

Neutral Plane

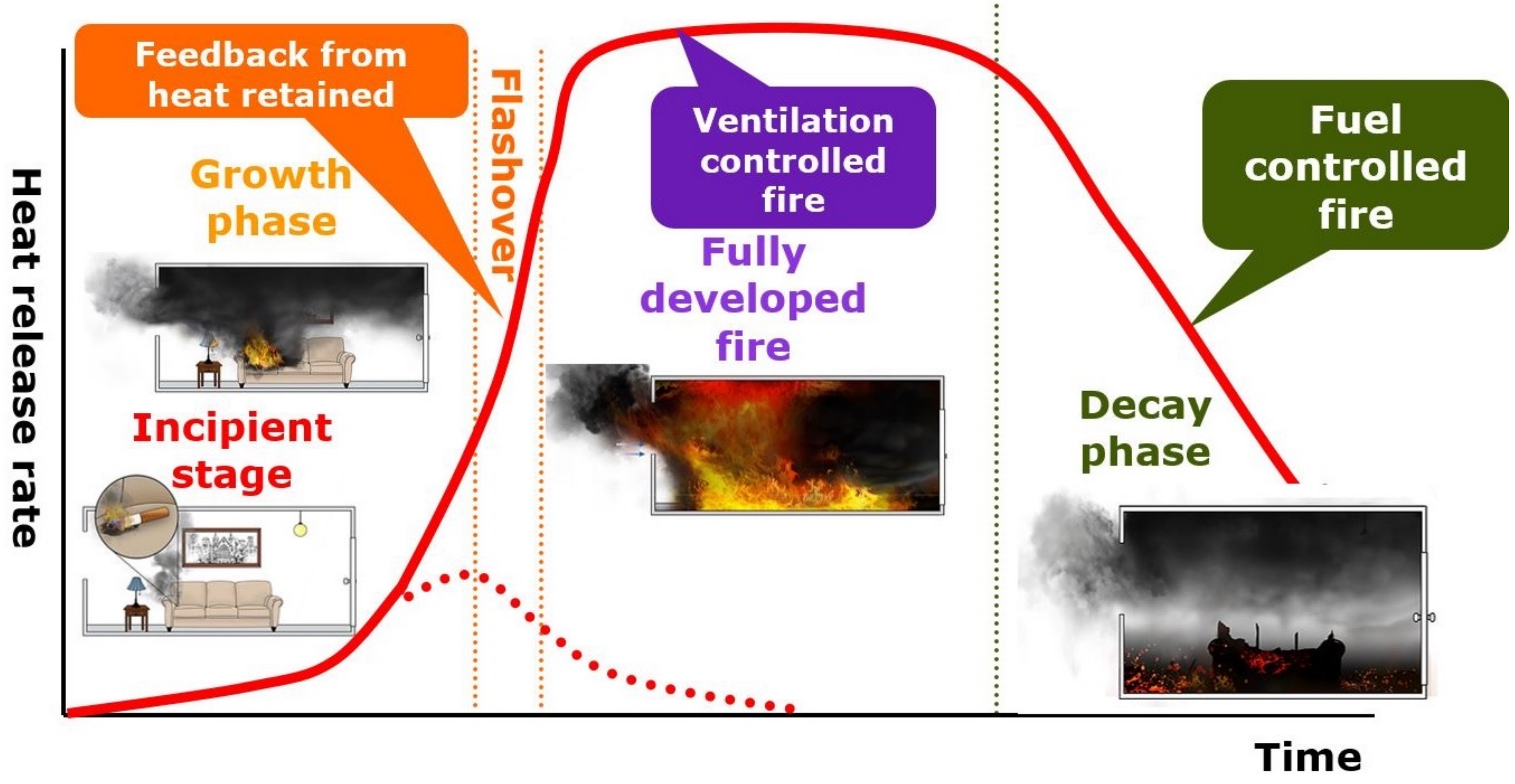
Post-Flashover

Compartment Fire Modelling - traditional

- Key aspect of fire and for urban fire spread –

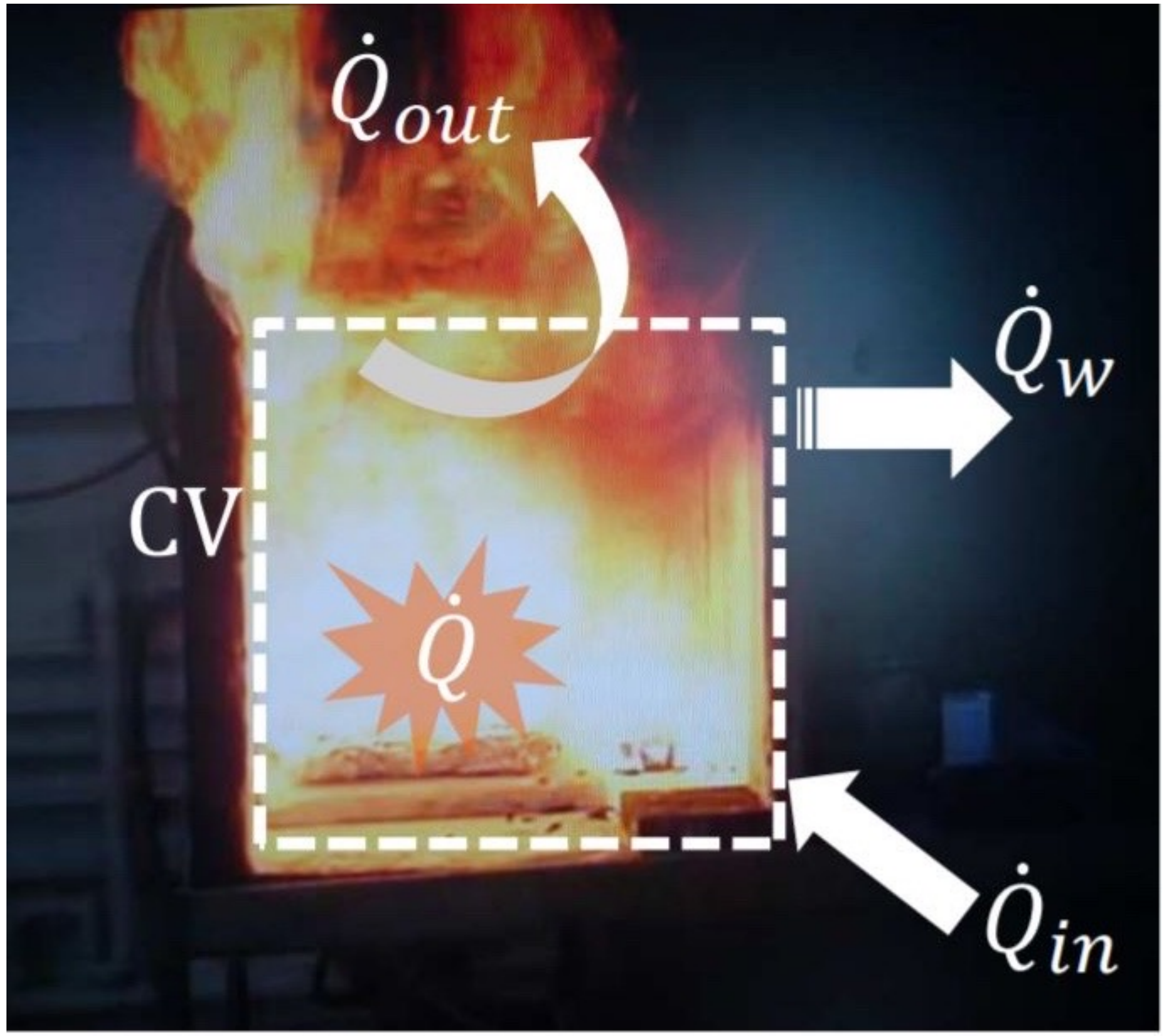
  when does fire grow to being ventilation controlled

- How can we model the compartment fire?
- Lots of experiments over decades
- Ventilation (access to O_2) is key



Compartment Fire Modelling - traditional

- Many models for estimating the energy release rate and temperatures of fire
  - MOST about **energy balance** (and thus **conservation of mass** of fuel that is pyrolyzing)
  - SFPE handbook –
    - 5 pre-flashover methods
    - 5 post-flashover
    - 3 methods of predicting flashover
  - Drysdale intro to fire dynamics
  - **Knowledge predominantly based on thermally thick, non-combustible, sealed boundaries, with approx. cubic geometry**



SFPE Handbook (vol 1., 5th ed. – pg 982)

Compartment Fire Modelling - traditional

- Through assumptions and experiments

$\dot{m} = 0.09\ V_f$

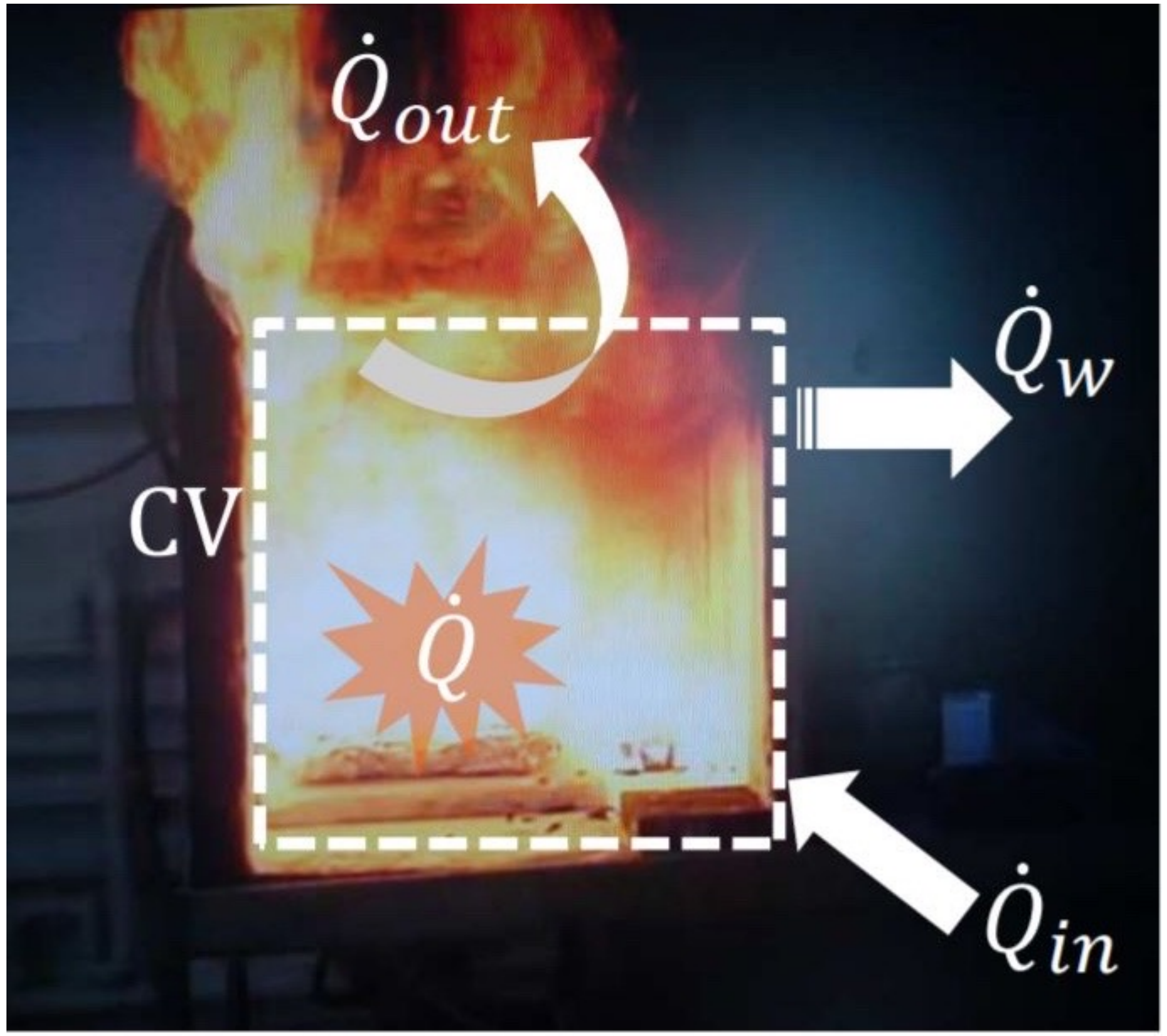
$T_{g,max} = \frac{6000\ (1-e^{-0.1\cap})}{\sqrt{\cap}}$ Where $\cap = \frac{A_T - A_W}{V_f}$

Max HRR $= 0.09\ V_f \Delta H_{c_{wood}}$

$\dot{q}_{fo} = 610(h_k A_T V_f)^{1/2}$ (assume flashover at 525˚C)

h_o/H = 0.3 - 0.5

What happens if not thermally thick?



SFPE Handbook (vol 1., 5th ed. – pg 982)

Formal vs informal compartments

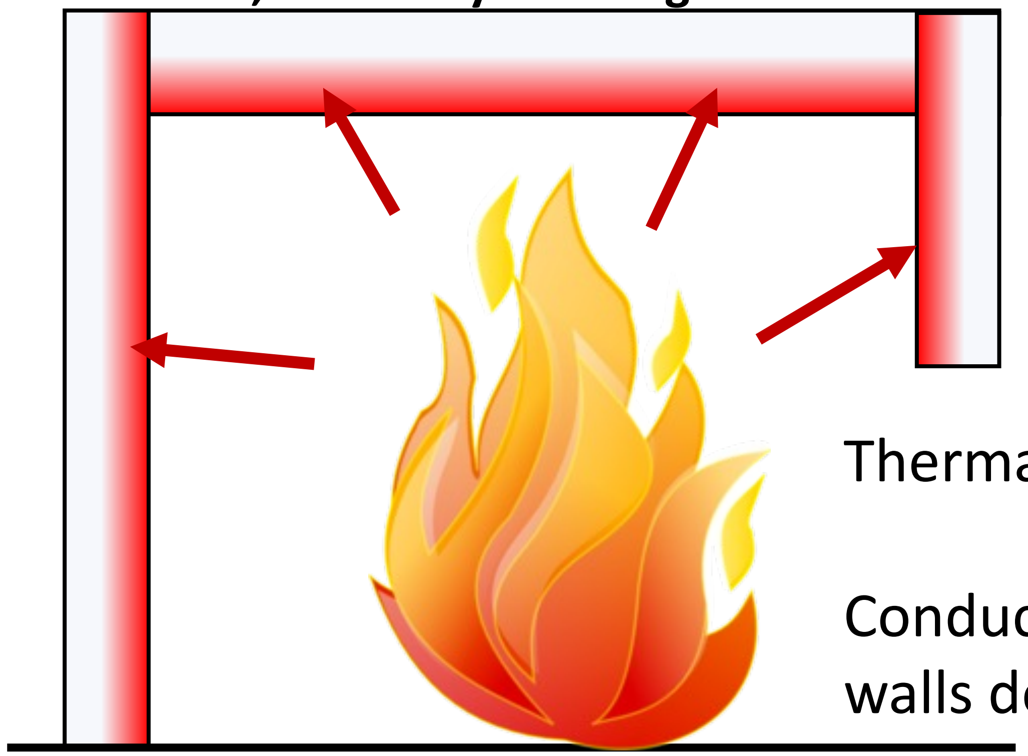
- **Fuel** – unregulated high fire loads. e.g., non-FR rated PU foam mattresses.
- **Combustible wall linings** - e.g., exposed cardboard or wood for insulation.
- **Control Volume boundary conditions**
  - Thermally-thin bounded compartments. e.g., corrugated steel walls, roof < 1 mm.
  - Leakages between at construction joints and heating deformation.
  - Sudden change in ventilation. e.g., structural collapse of wall during fire

Thermal thickness

$$Biot\ number, Bi = \frac{hL}{k}$$

- h: Convective heat transfer coefficient (W/m^2K)
- L: Thickness (m)
- k: Thermal conductivity (W/mK)

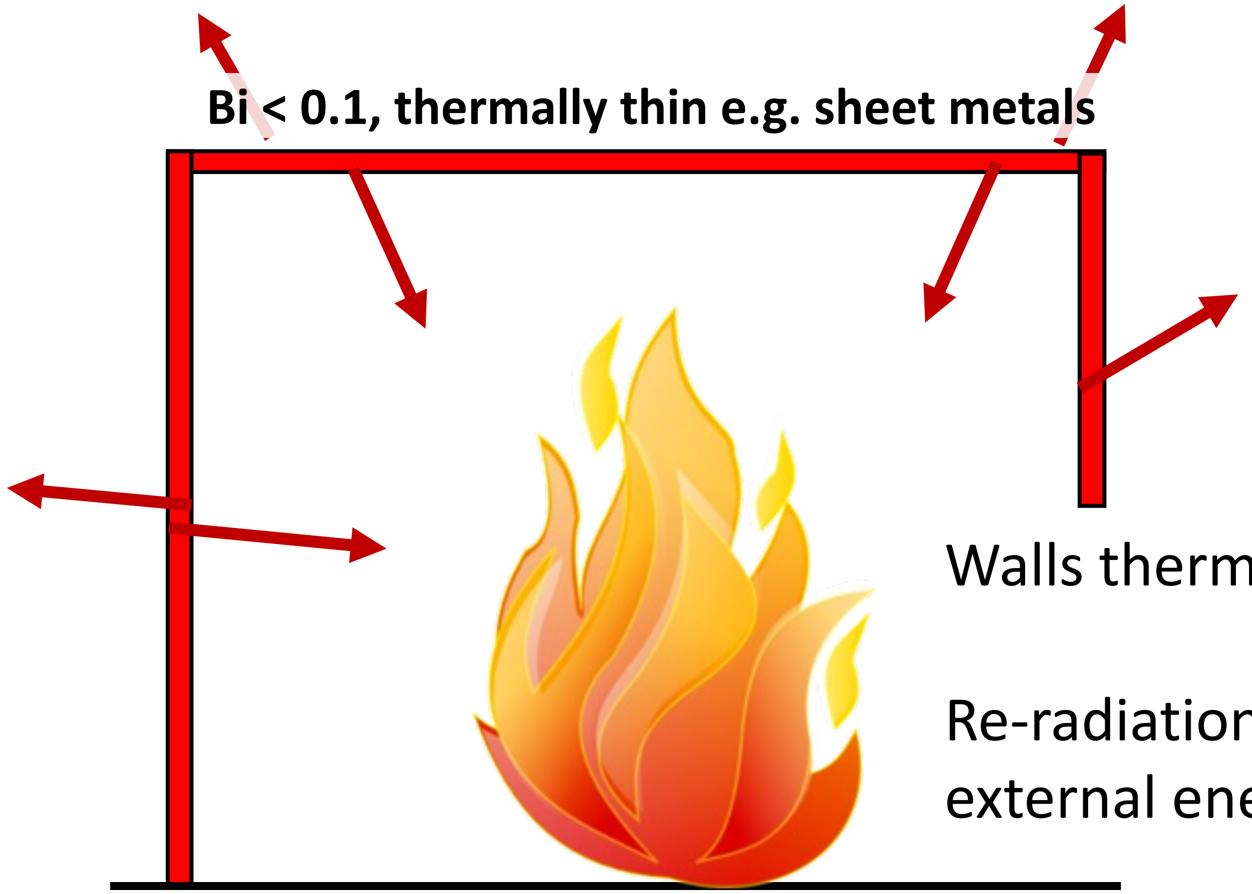
Bi > 1, thermally thick e.g. concrete



Thermal gradient in walls

Conduction and storage in walls dominate

Bi < 0.1, thermally thin e.g. sheet metals

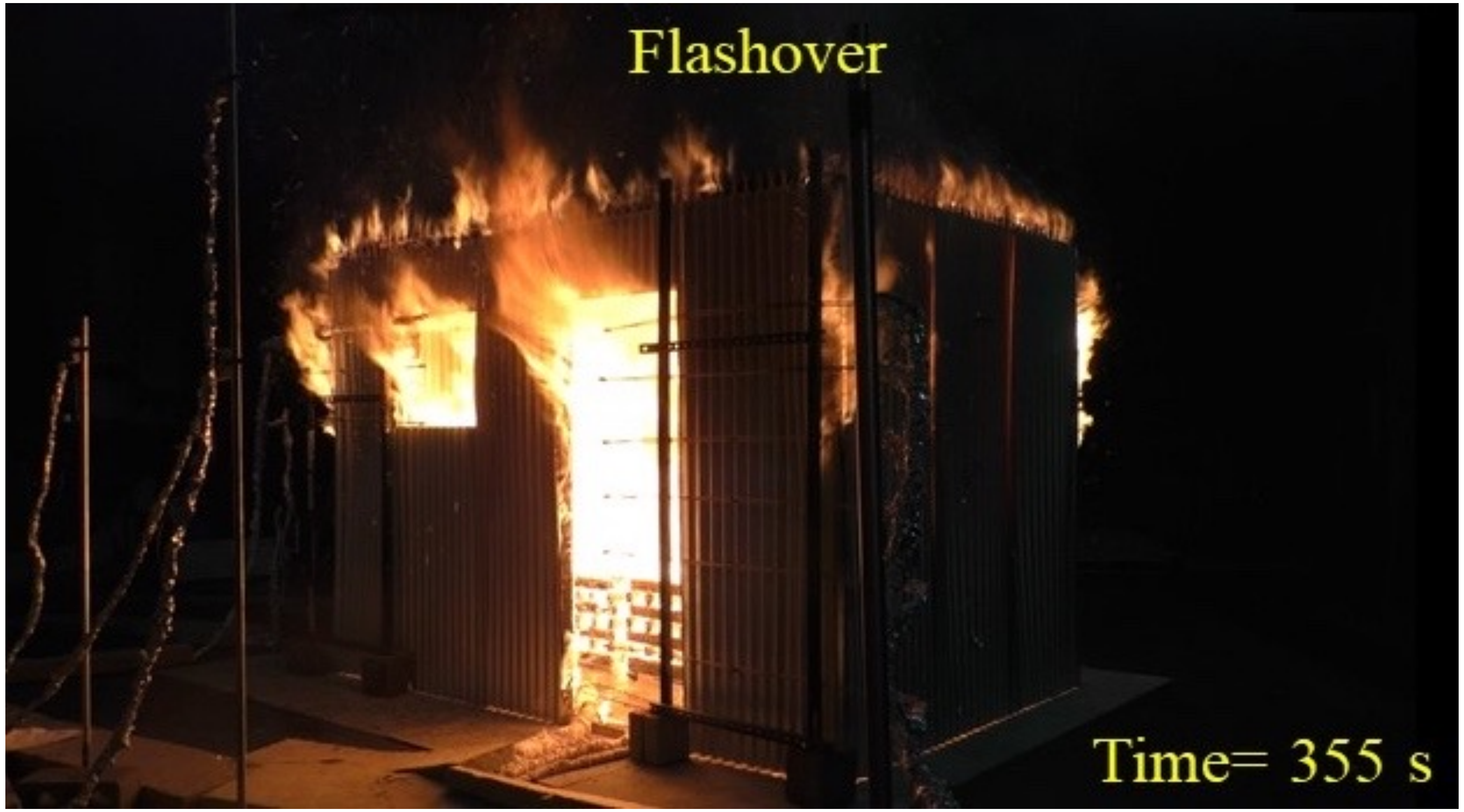


Walls thermally penetrated

Re-radiation to fuel and external energy losses

Boundary conditions impacts - internal?

Boundary conditions impacts - internal?



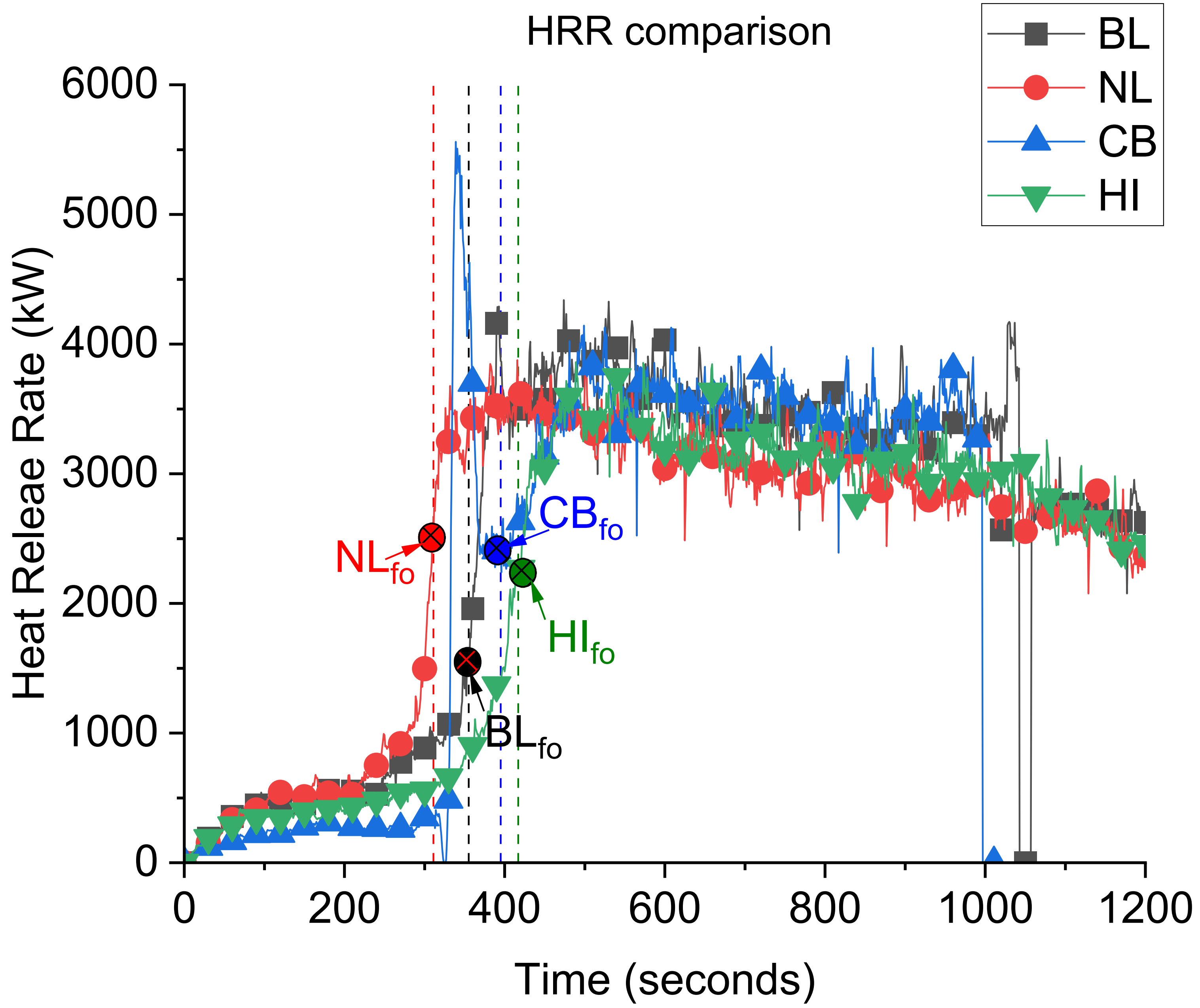
Gas temp at flashover – 420˚C
23% less than 525˚C
Max HRR – 4.3MW
approximately correct
Max Temp – 965˚C
emp. eq – 1210˚C
Neutral plane – 1.05m
emp. eq. – 0.75m

Why? Heat losses through boundary and/or through leakages at joints?

Boundary conditions impacts - internal?

- Comparing HHR from 4 similar experiments
  - BL – Baseline
  - NL – no leaks
  - CB – carboard lined
  - HI – highly insulated
- NL – first to FO
- HI – slowest to FO

- Energy stored in insulation > Energy lost through walls
- .: more energy being reradiated to fuel in t-thin comp.



Large-scale experiments

Boundary conditions impacts - internal?

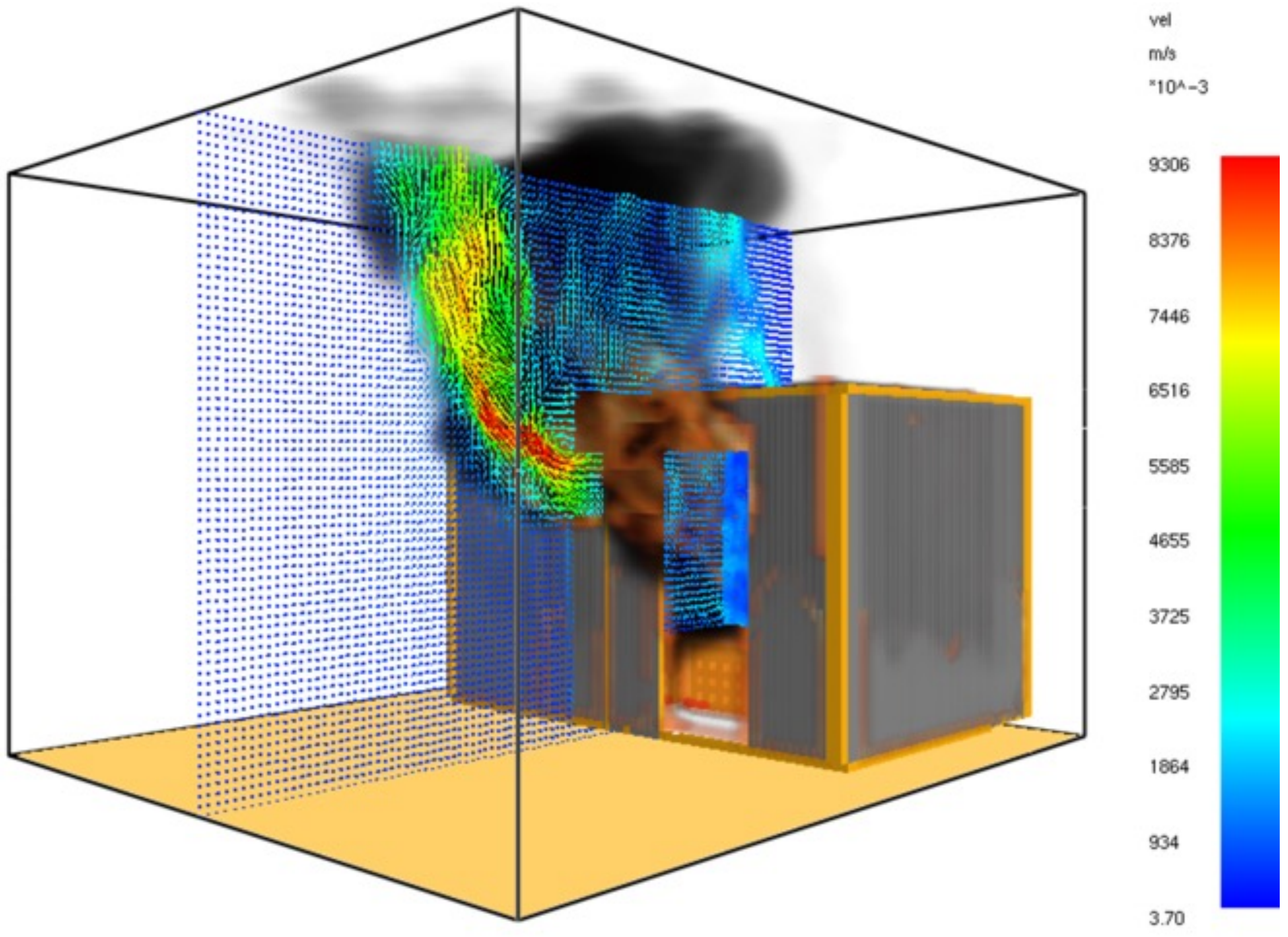
- Through modelling of experiments we can determine new equations
  - Thermally – thick

$$\dot{q}_{fo} = 610(h_k A_T V_f)^{1/2}$$

  - Thermally – thin

$$\dot{q}_{fo} = 1442[\varepsilon A_T V_f]^{0.173}$$

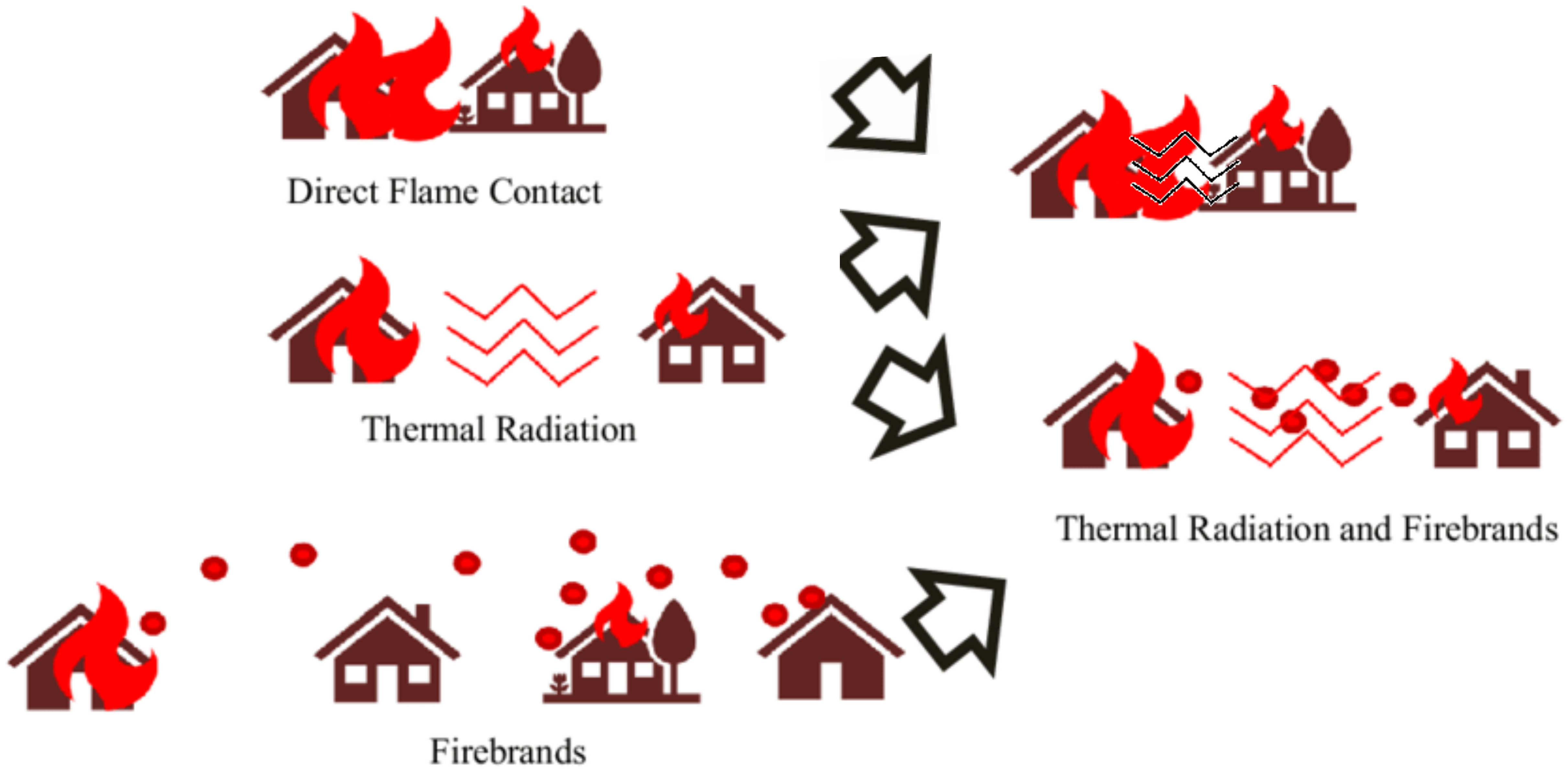
- Work is ongoing to determine more empirical corelations



Summary of internal fire dynamics

- Lots of knowledge on well-sealed, thermally thick compartments
  - Thus lots of models
- Using same empirical equations for thermally thin, leaky compartments overestimate values
  - Apart from Max HRR
- Emissivity, rather than thermal inertia, of boundary key to understanding dynamics for ISDs
  - Heat losses from boundary
  - Re-radiation in compartment

Structure to structure fire spread



Suzuki, Sayaka & Manzello, Samuel. (2020). Investigating Coupled Effect of Radiative Heat Flux and Firebrand Showers on Ignition of Fuel Beds. Fire Technology. 57. 10.1007/s10694-020-01018-5.

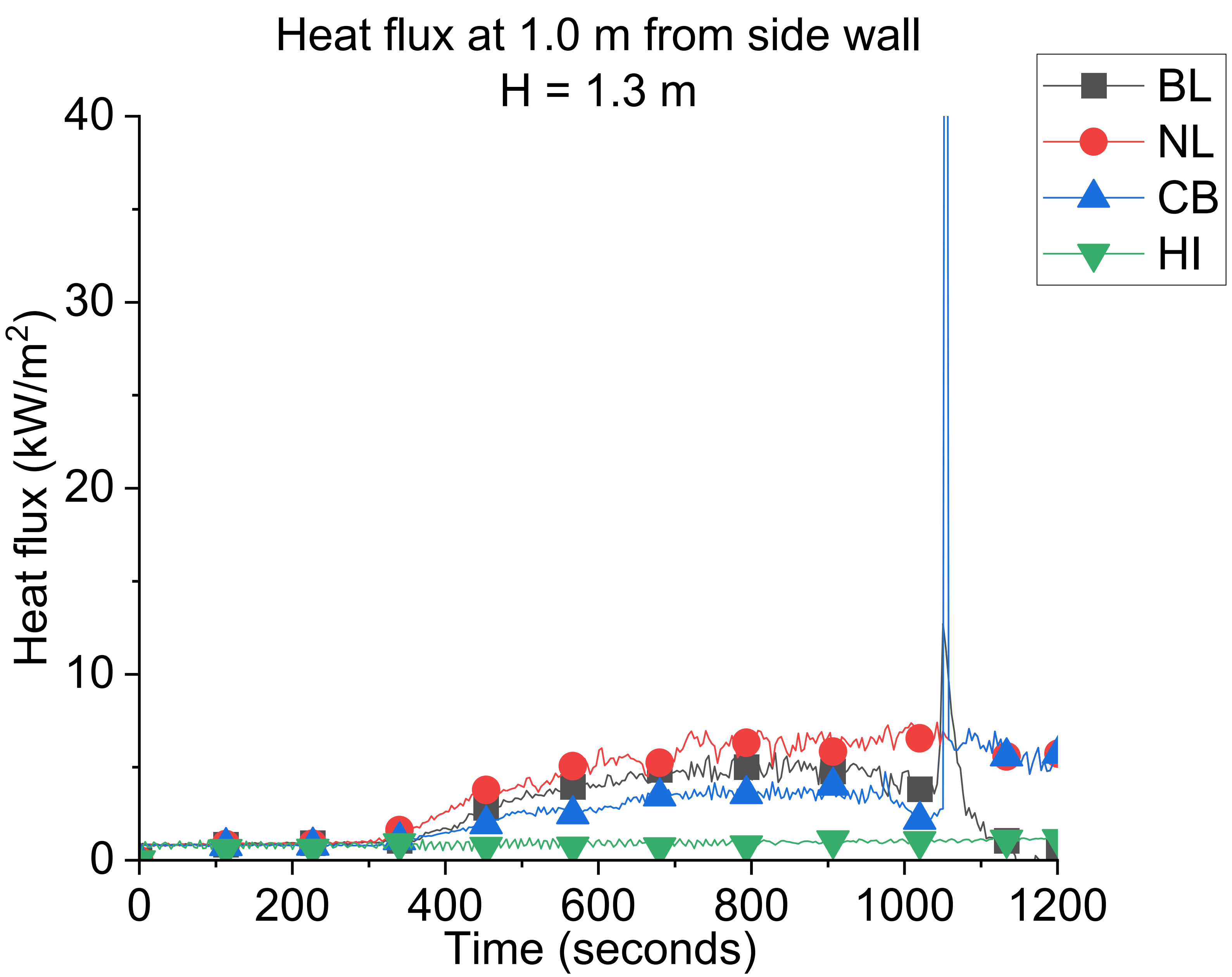
Radiation from thermally thin compartments

- Basics – walls and openings
- Comparing HHR from 4 similar experiments
  - BL – Baseline
  - NL – no leaks
  - CB – carboard lined
  - HI – highly insulated

Radiation from thermally thin compartments - walls

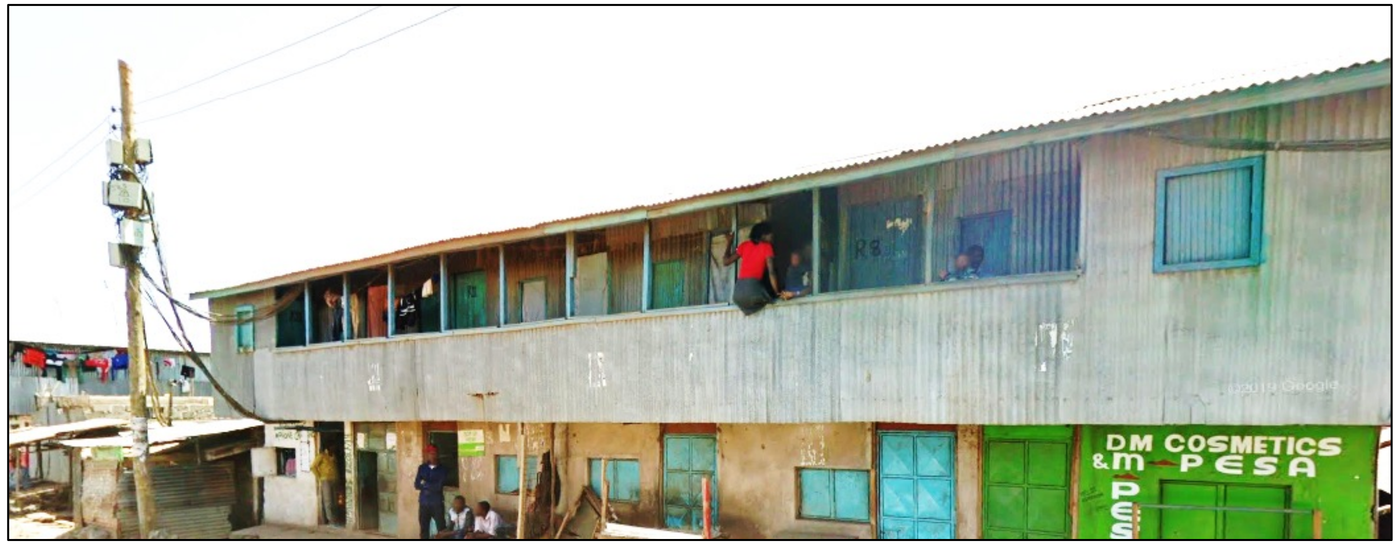
- NL – highest at about 6-7 kW/m^2
- BL & CB – 4-6 kW/m^2
- HI – 1 kW/m^2

- NL – gases kept for longer in compartment – greater heating of steel walls
- Not going to ignite another structure

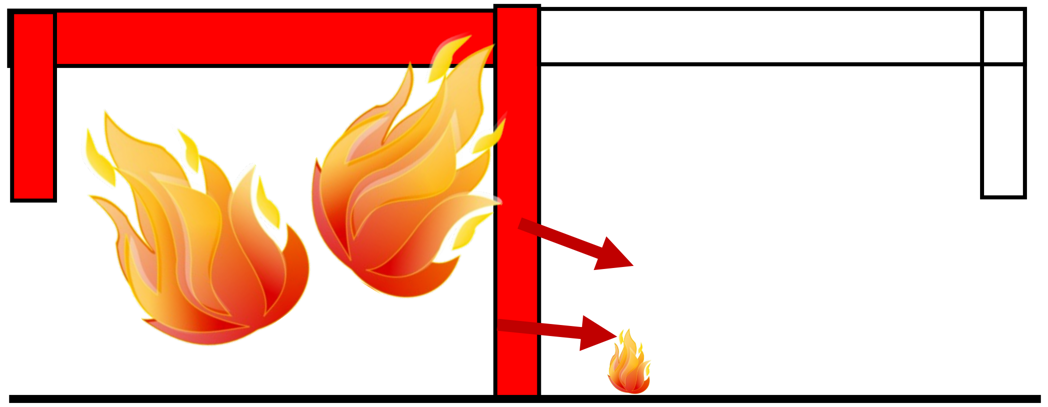


The fire dynamics – external heating

External plume



Adjacent compartment flashover

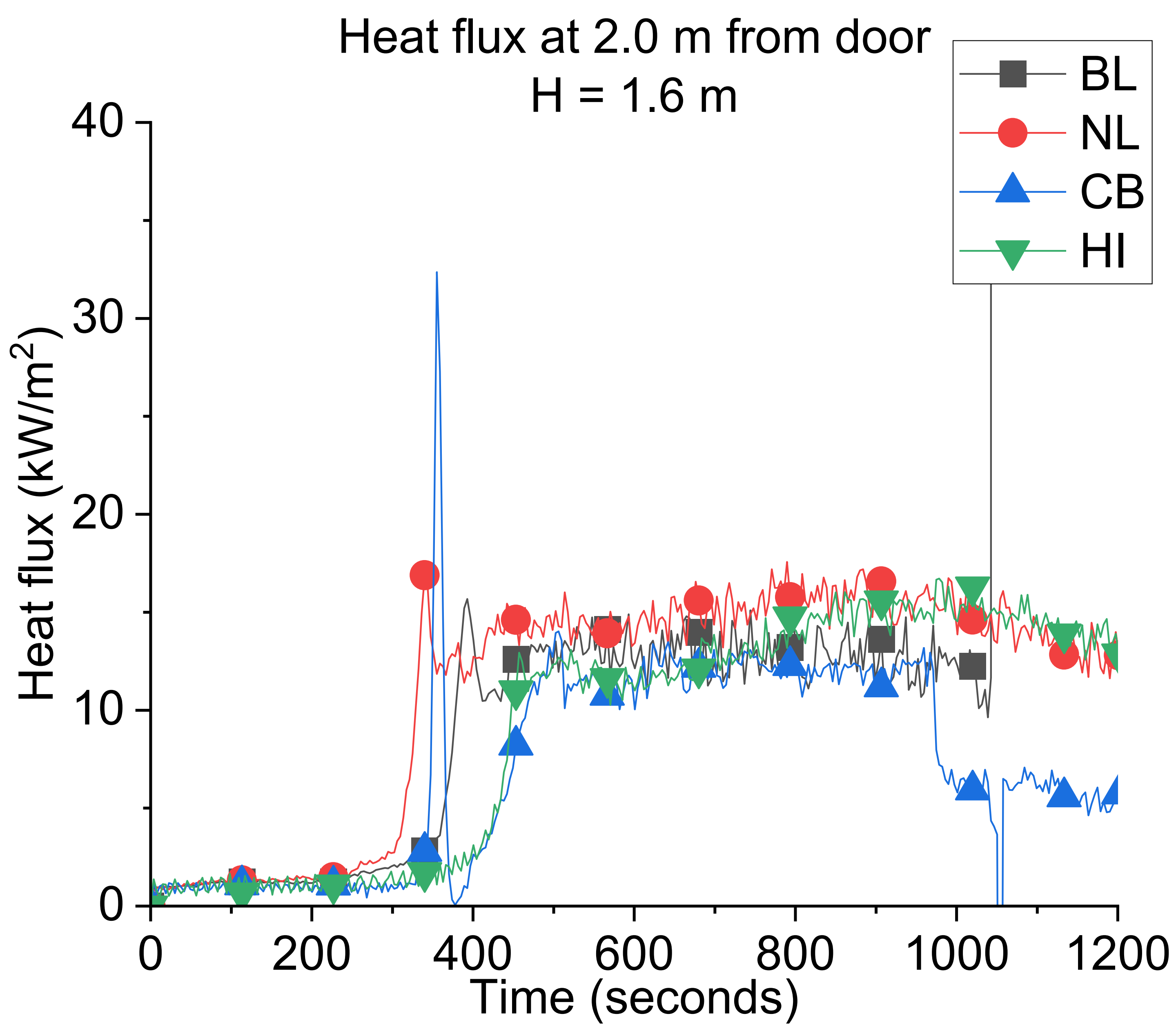


What changes here?
Up to 45% faster flashover
Depends on internal ignition (happens through small gaps) and external flux level

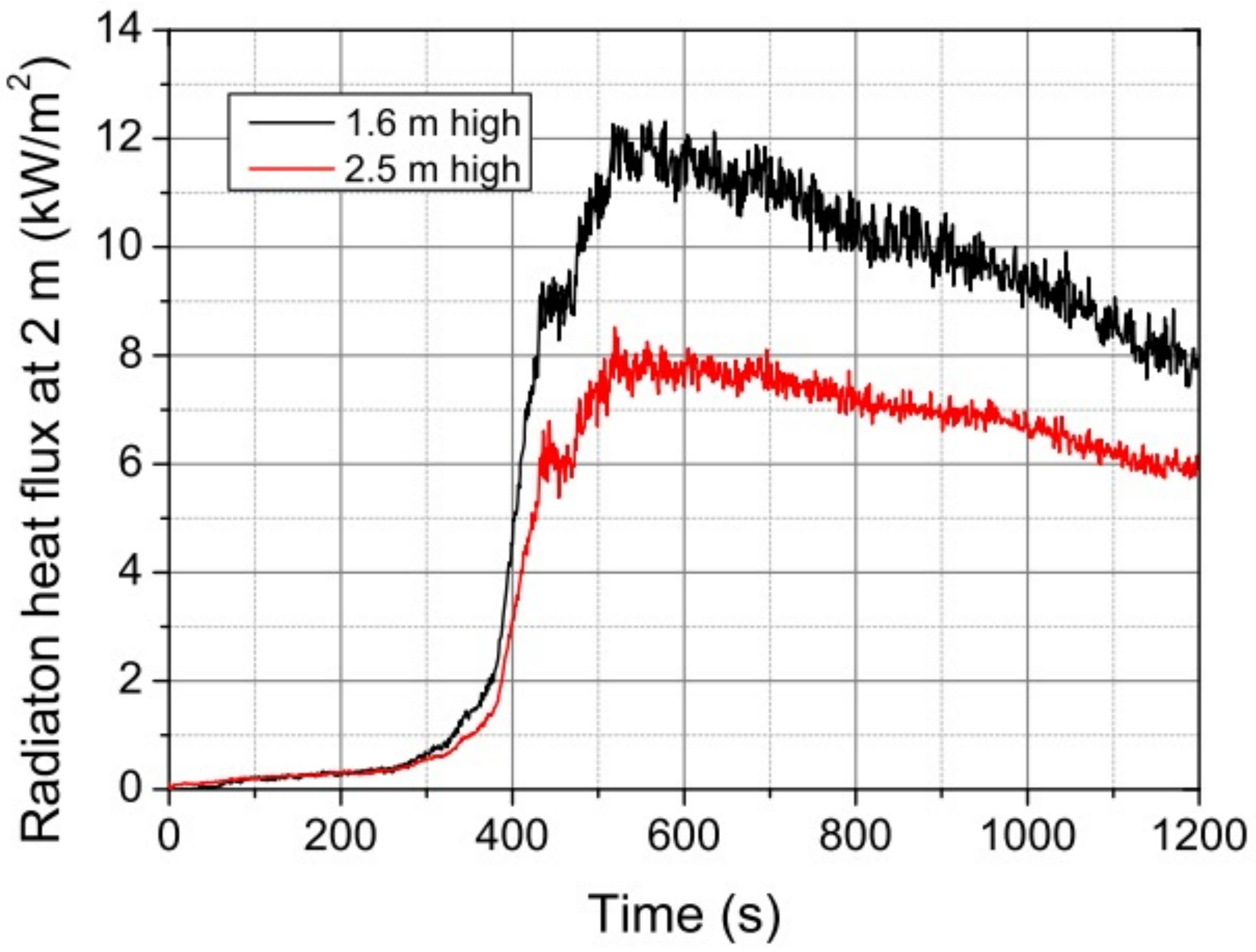
Radiation from therm. thin compartments - openings

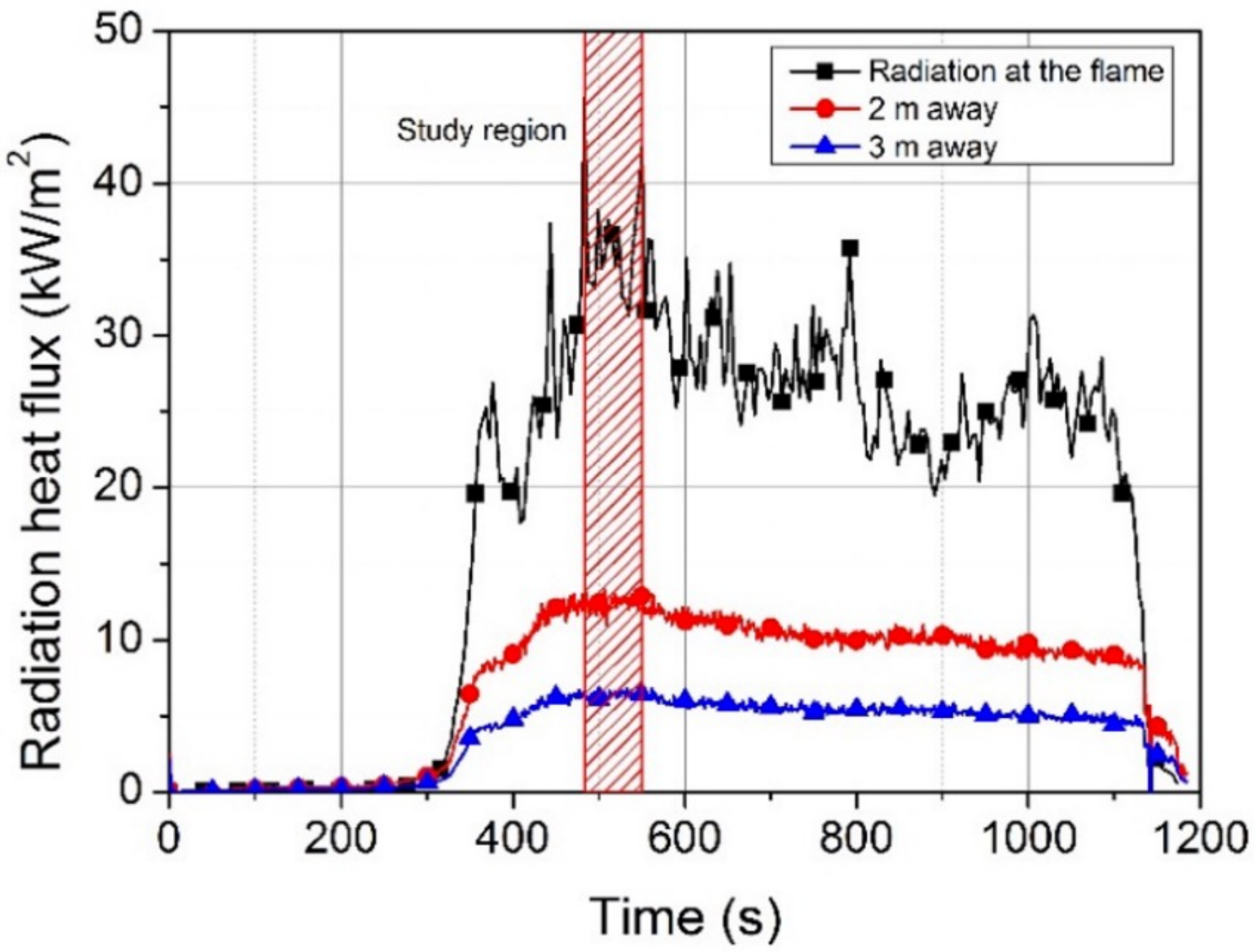
- NL – highest 14-15 kW/m^2
- BL & CB – 12-13 kW/m^2
- HI – 14-15 kW/m^2

- NL & HI – gases only can escape through openings – greater flux.
  - Higher temps inside
  - Longer/larger flames



How does flux change with height and distance

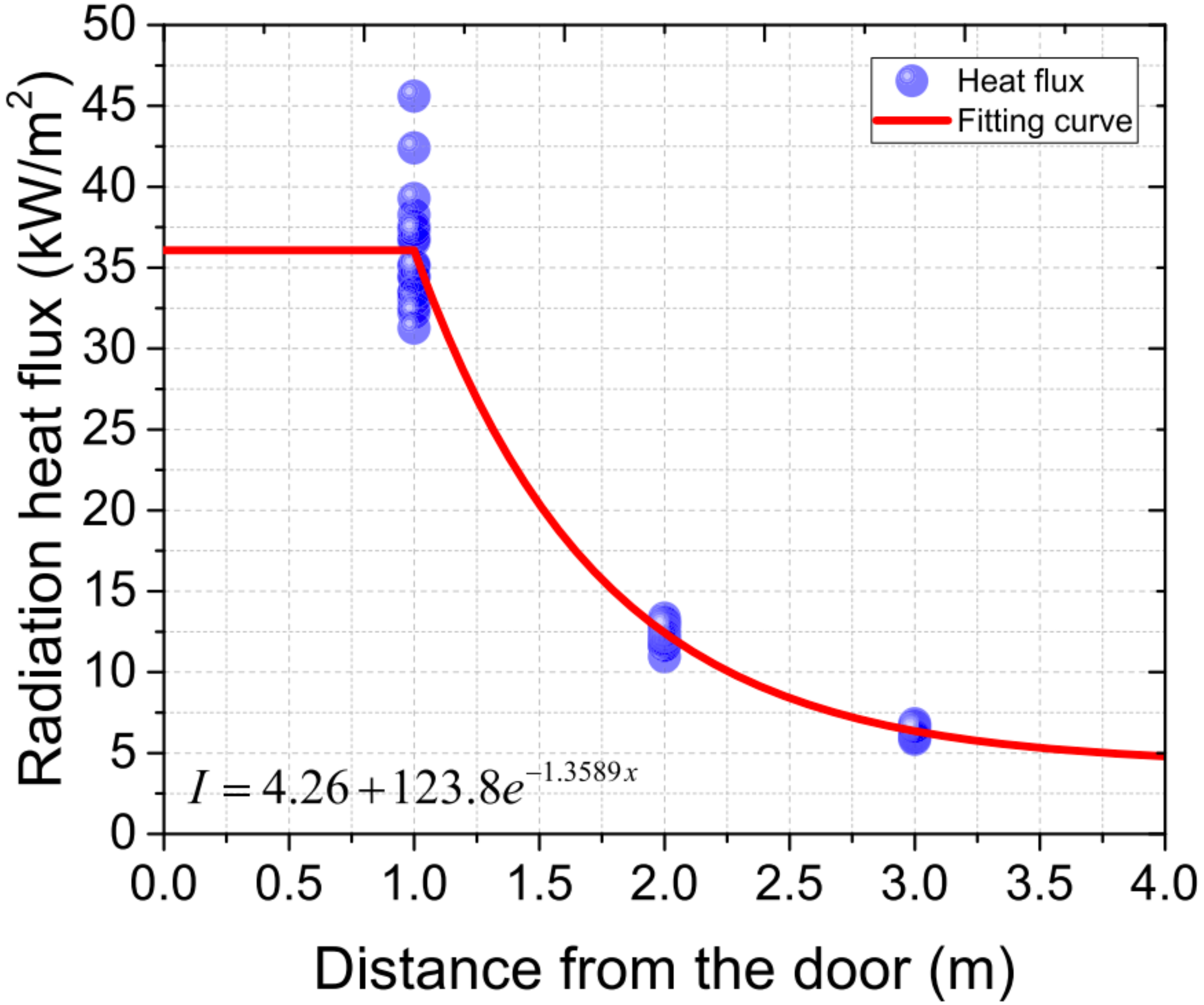




Note: slightly different test set-up being presented – using watercooled HF gauges, rather than thin-skin calorimeters and larger window involved.

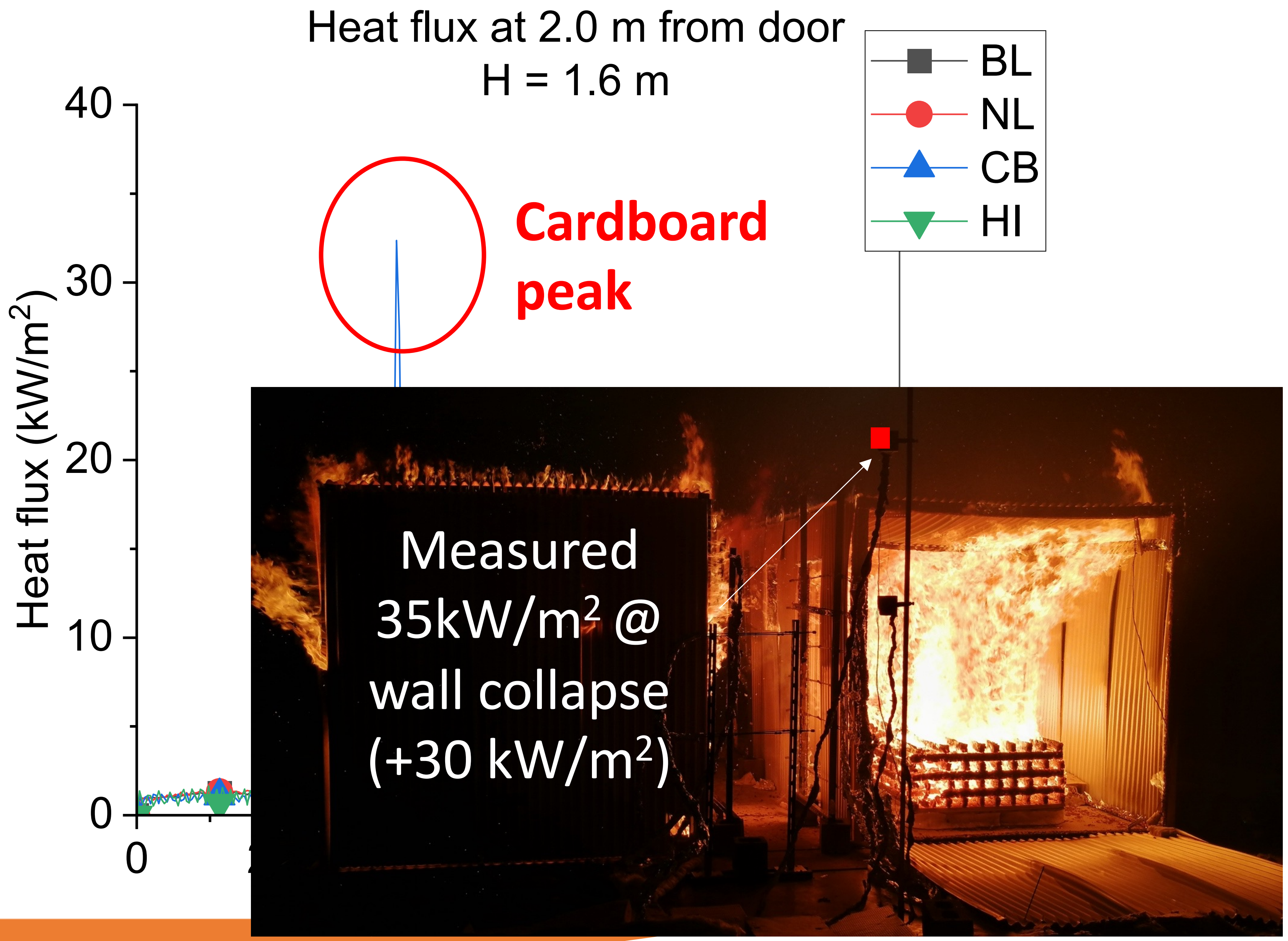
How does flux change with height and distance

- Making assumption about how far the flame extends – 1m
  - Fit curve after 1m
- Flux measured opposite door (door and window on same side)
  - If window is on another wall – 2.0m & 3.0m values go down (but only down 1-2 kW/m^2 @ 2m)



Radiation from thermally thin compartments

- Assumptions
  - Just wood burning
  - Cardboard – large instant flux
- No distortion or collapse of walls/roofs
  - Distortion – increased ventilation area – decreasing flows at door
  - Wall/roof collapse – large instant flux not out of door

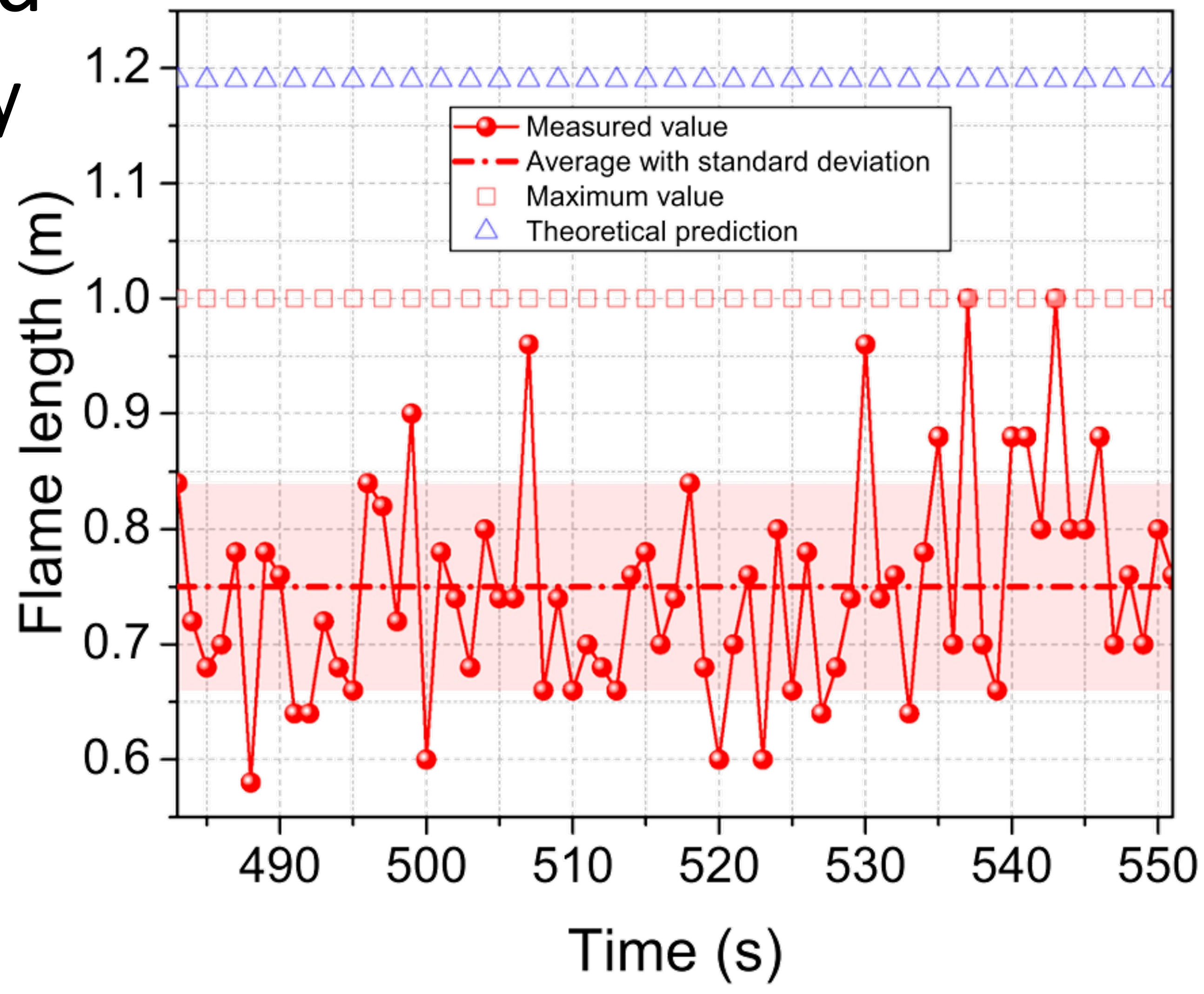


Flame lengths (no wind)

- In general – for a single structure – no wind
  - Flame lengths lower than theory for thermally thick compartments,

$$L = 0.6h\left(\frac{z}{h}\right)^{1/3} + \frac{h}{3}$$

$$z = 12.8\left(\frac{R}{w}\right)^{2/3} - h$$



h,w= height, width of opening

R = average burning rate (mass/time)

Depends on leakage also – NL slightly longer flames

Materials and ignition

- Spontaneous ignition of materials from external HF
  - Very unlikely unless very close to opening
  - Or large conflagration already underway (many buildings on fire simultaneously)
  - Likely to be piloted even in that case
- Database created – from ISD materials

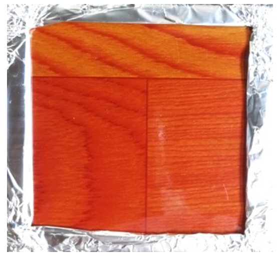

Carpet


Curtain


Blanket

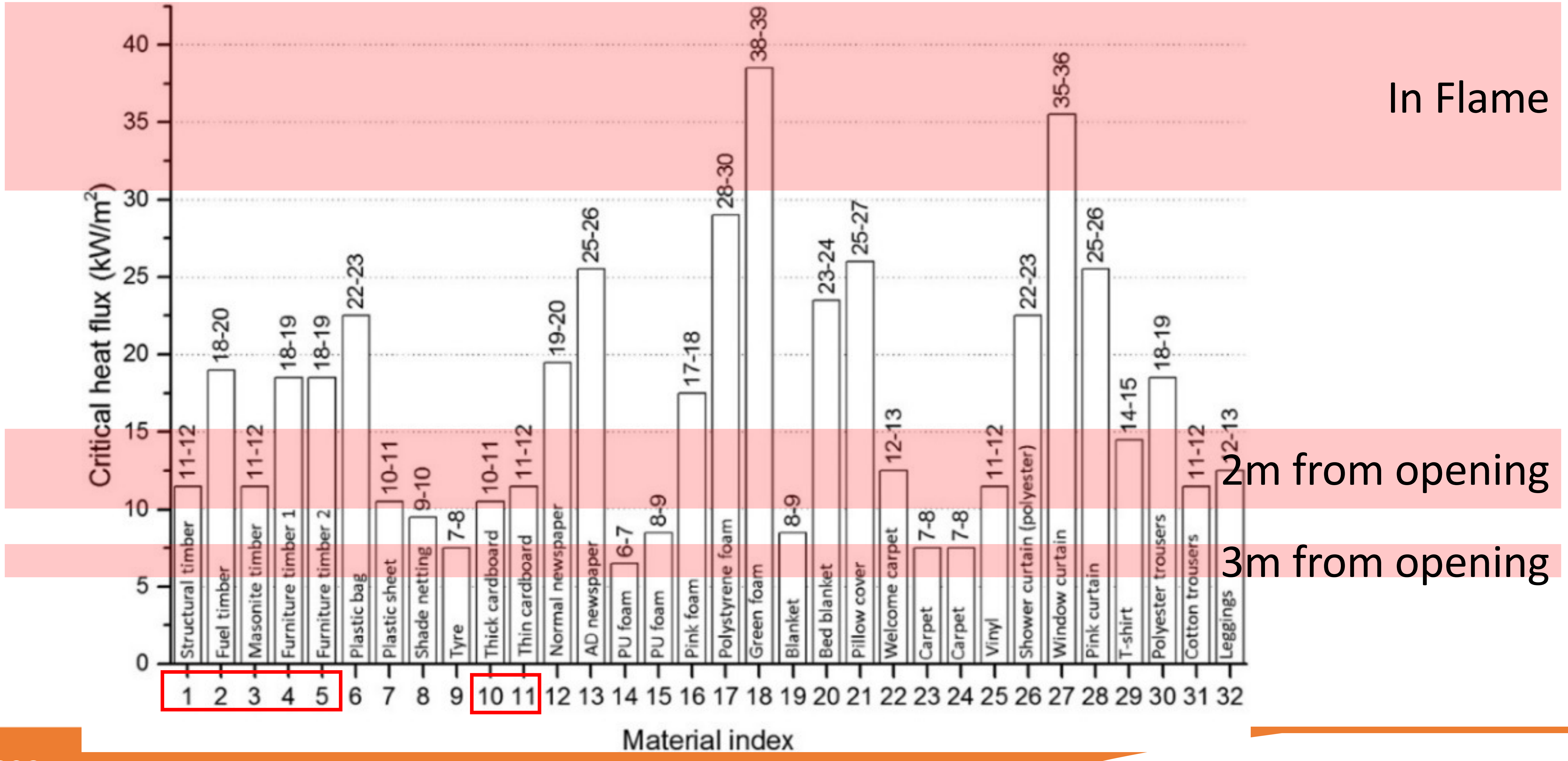

Local pine


Pillow cover


PVC floor covering

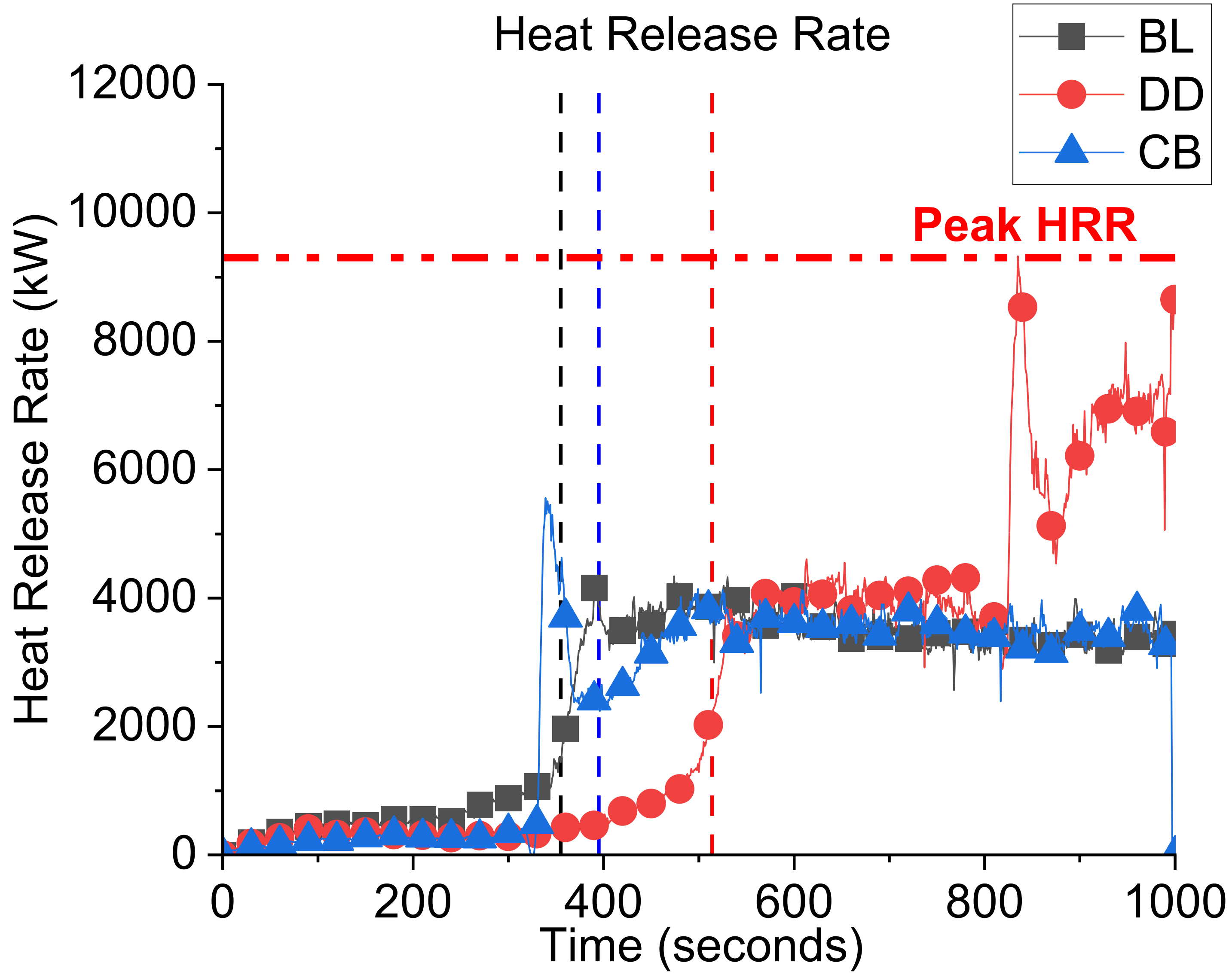
32+ different sample types
408+ experiments total to date

Piloted ignition CHF database

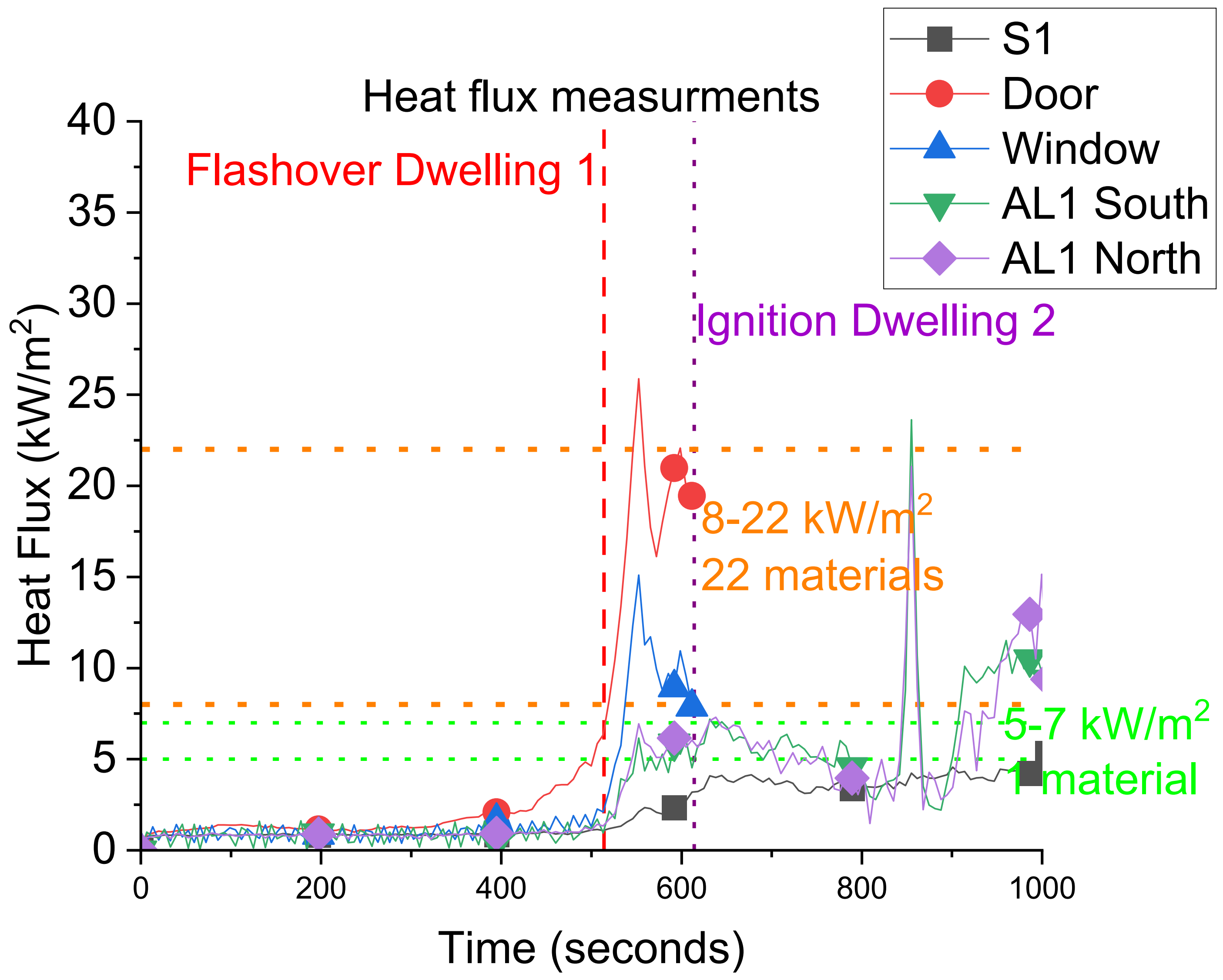


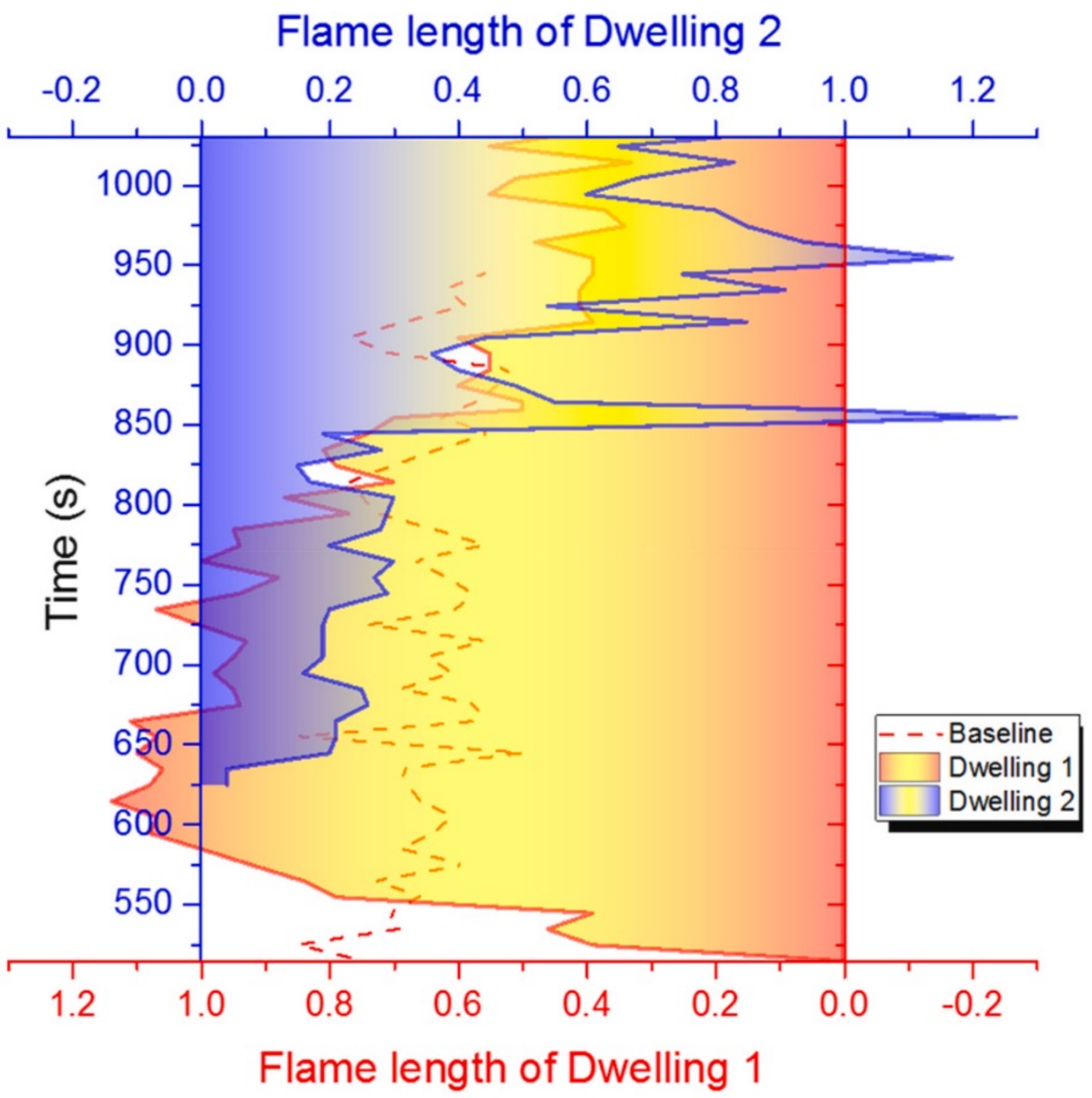
20 mins in cone under the higher heat flux caused ignition with a pilot

Double dwelling experiment in lab conditions



Two structure - fluxes and flame lengths



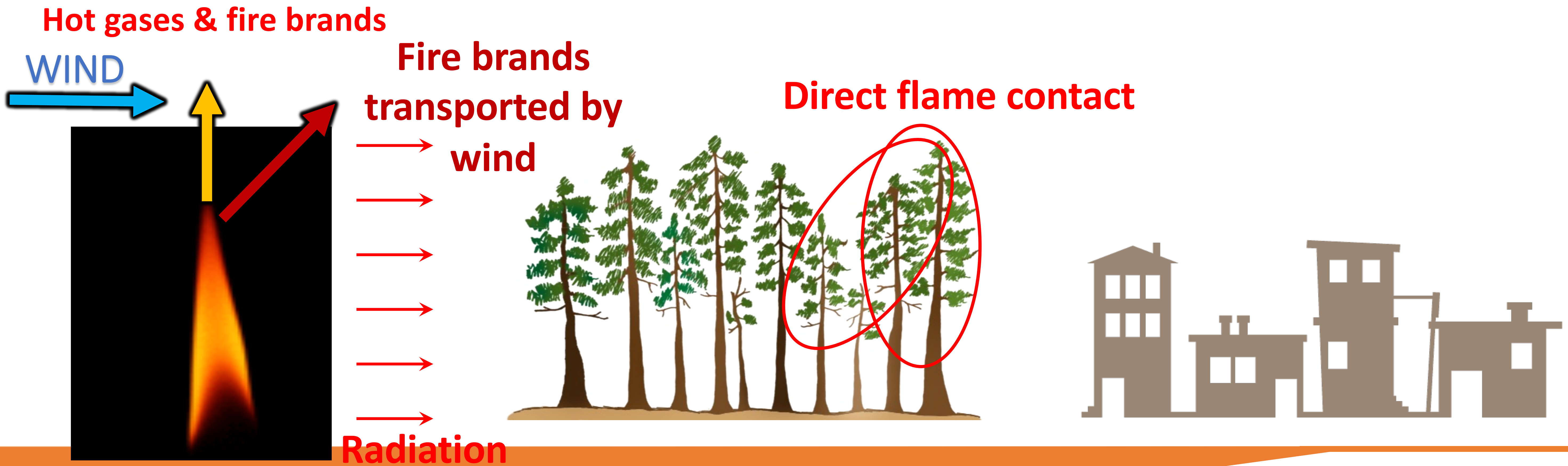


Summary of urban fire spread (no wind)

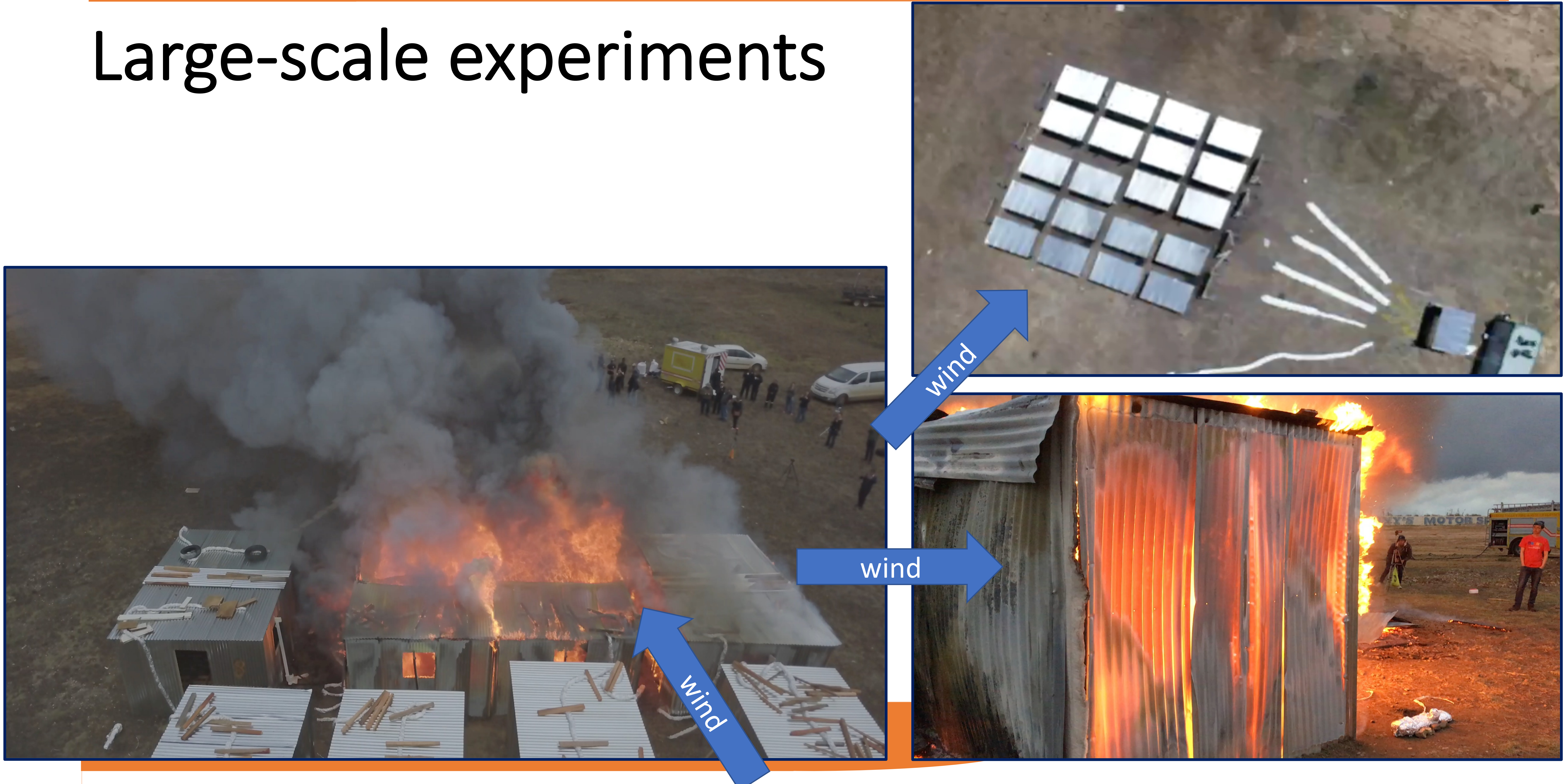
- Combination primarily of flame contact and radiation
- Based on compartment fire dynamics
  - This is complicated with leaky thermally thin bounded compartments
  - Reduced temps and times to flashover, smaller flames out of large openings compared to thermally thick
  - Close proximity of structures (not seen in formal environs) increases flame lengths
  - Connected thermally-thin compartments – need to consider pre-heating of environment

Influence of wind on urban fires

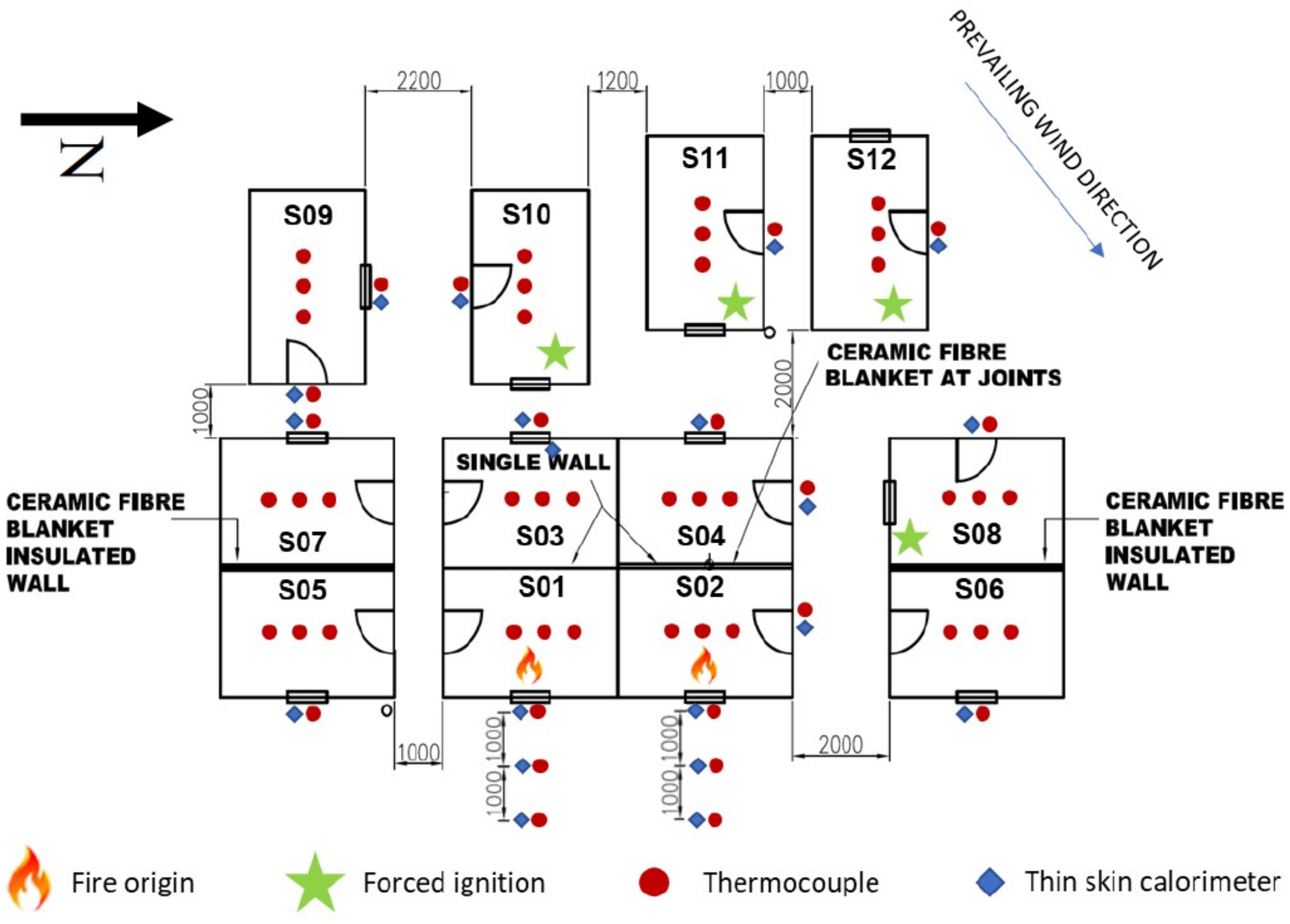
- Differences and similarities
  - Distribution of fuel (ladders, discontinuities, variety of topography etc…)
  - How fires develop and spread – configuration important



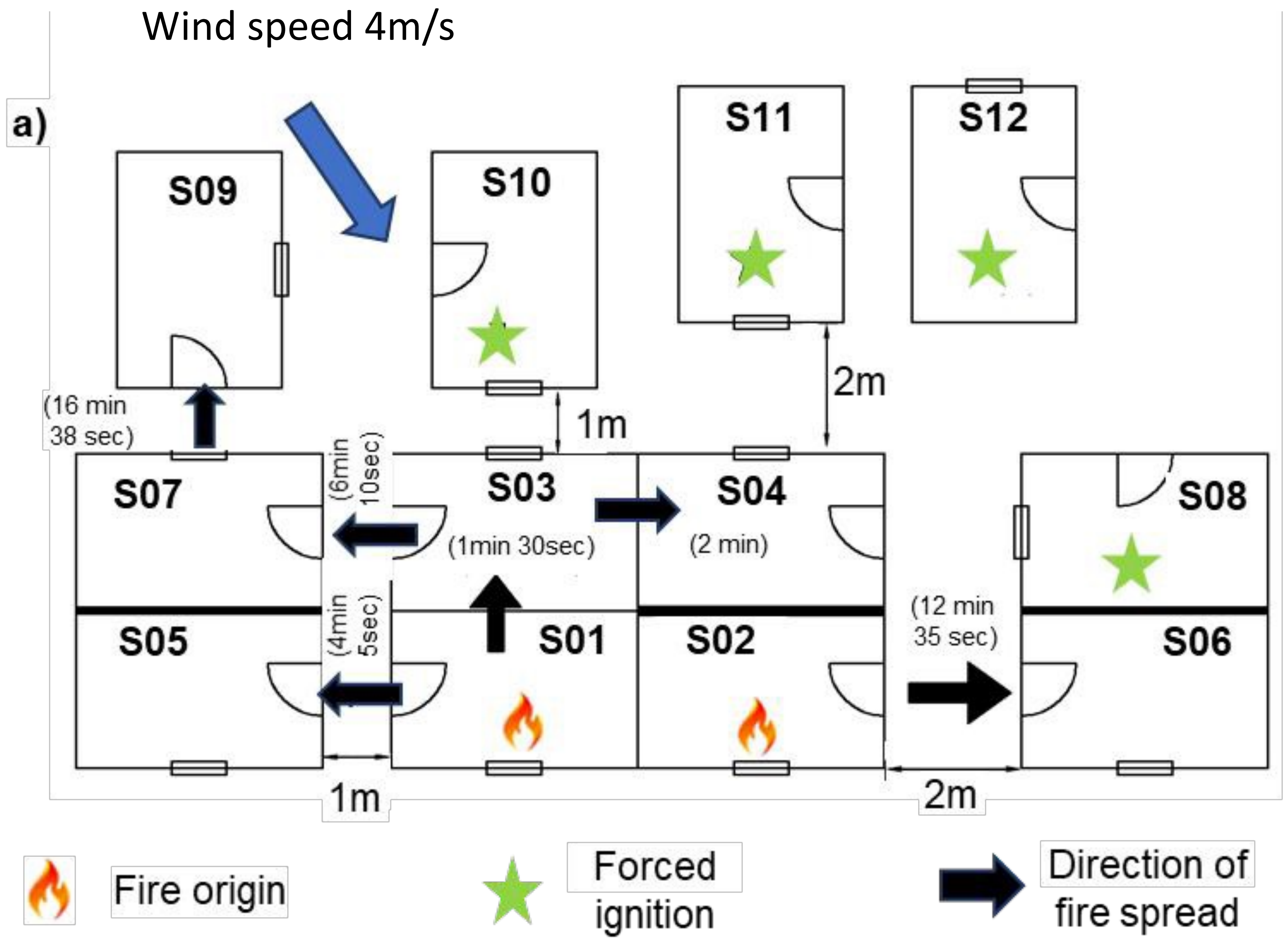
Large-scale experiments



Understanding from experiments – 12 Dwellings



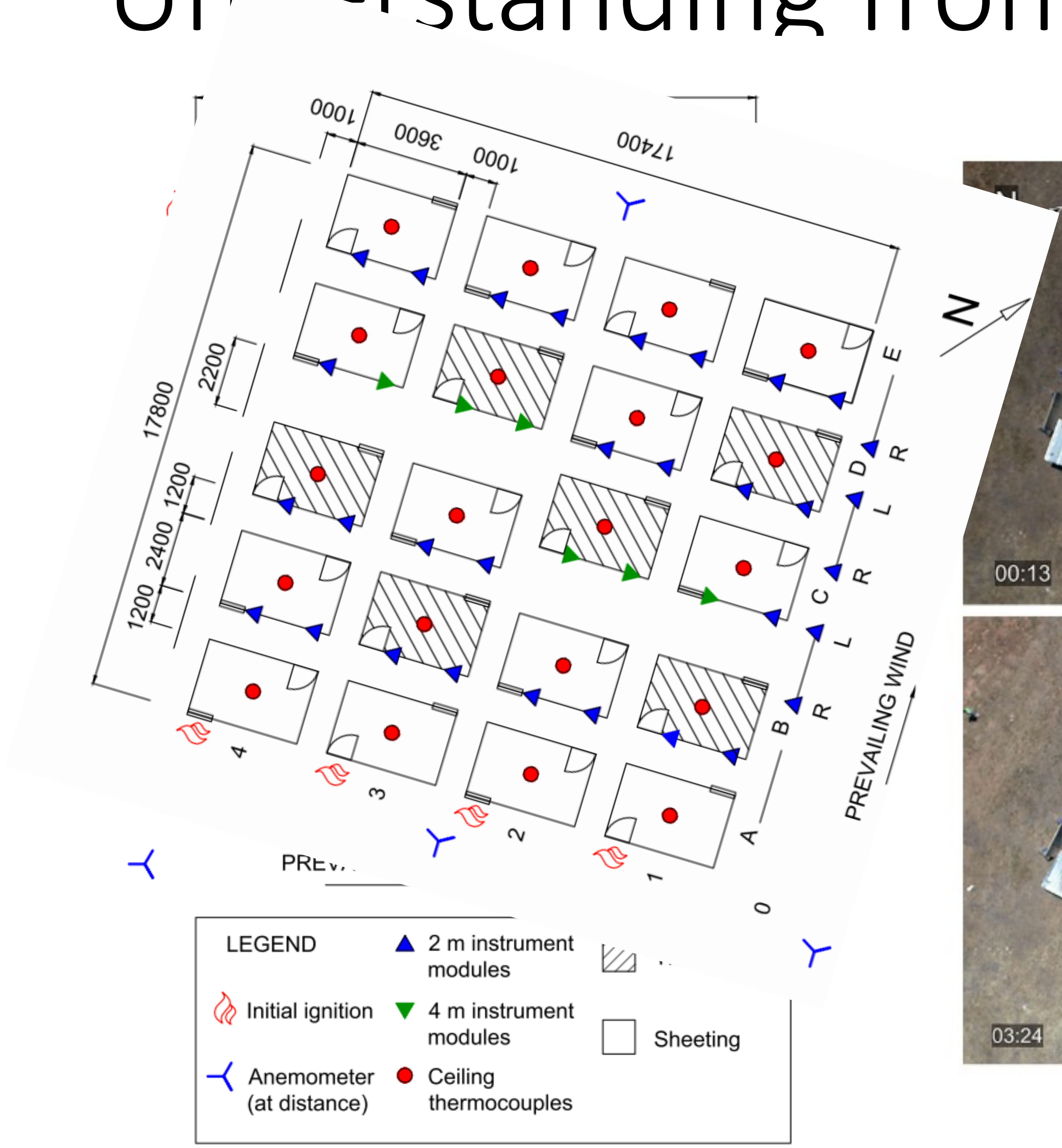
Understanding from experiments – 12 Dwellings

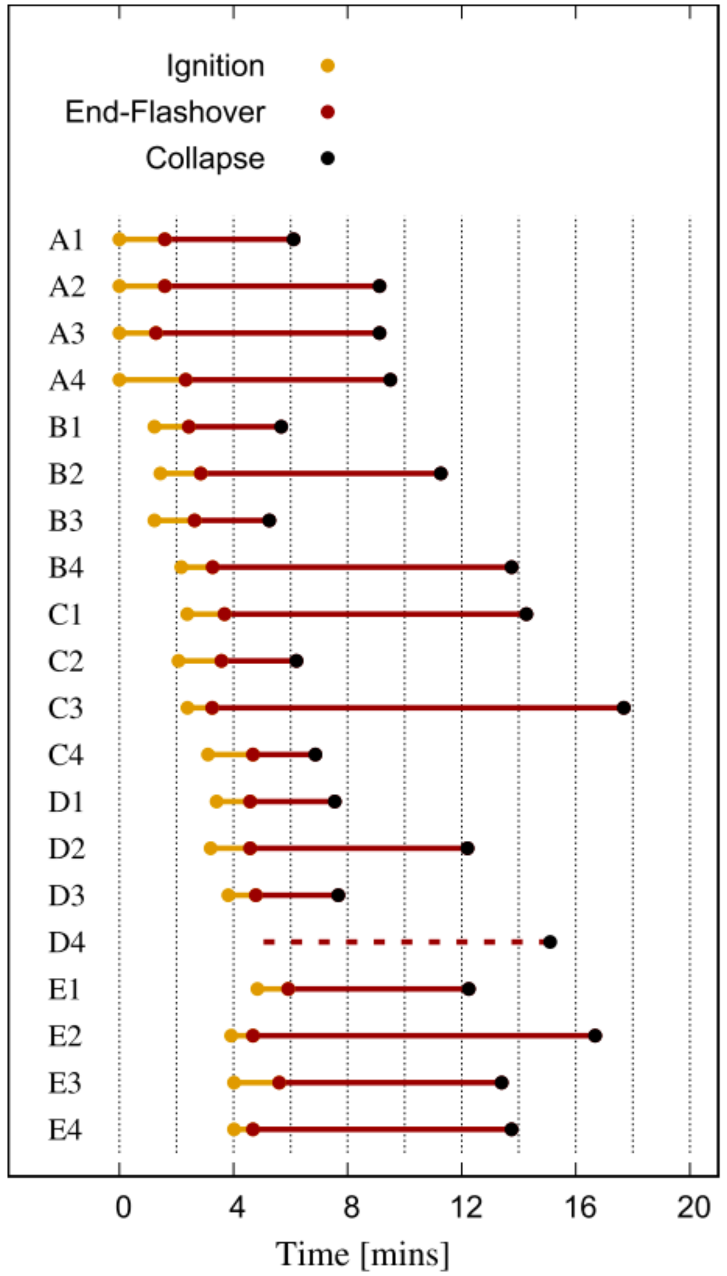


ISD No.	Ignition Time [mm:ss]	Time to Collapse (from ignition)	Time to flashover (from start) [mm:ss]	Ignited by	Flame exposure to ignition [mm:ss]
S01	00:00	10:15	03:55	Exp. start	-
S02	00:00	11:15	02:43	Exp. start	-
S03	01:30	09:10	04:48	S01 wall	-
S04	02:00	-	04:21	S01/S03 wall	-
S05	05:00	13:10	08:36	S01 flames	01:05
S06	12:35	08:50	15:09	S02 flames	09:52
S07	06:10	19:45	10:14	S03 flames	01:22
S08*	120:40	17:00	122:54	Forced ign.	-
S09	16:38	15:15	21:47	S07 flames	06:24
S10*	55:38	6:55	62:11	Forced ign.	-
S11*	65:31	76:21 (5:00)#	136:52	Forced ign.	-
S12*	99:00	3:22	105:32	Forced ign.	-

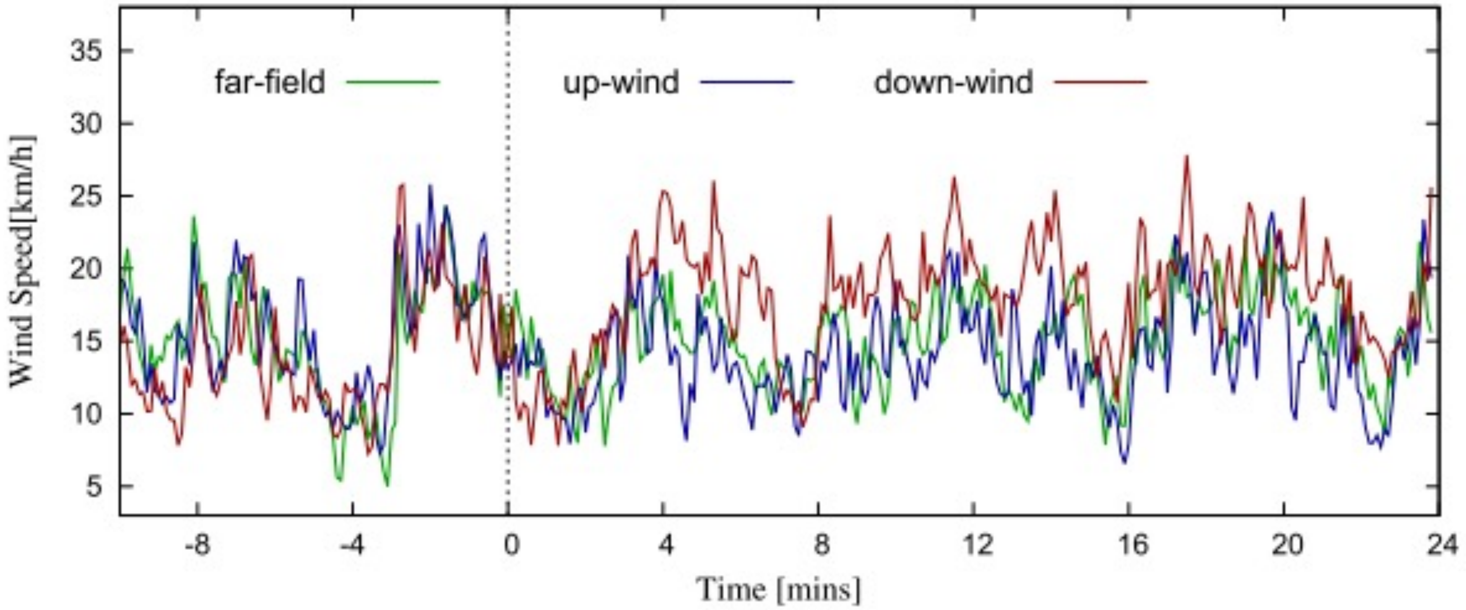
Gas layer temps	950-1100˚C
Door/window temps	800-1000˚C
Flashover	2-4 mins

Understanding from experiments - 20 dwellings



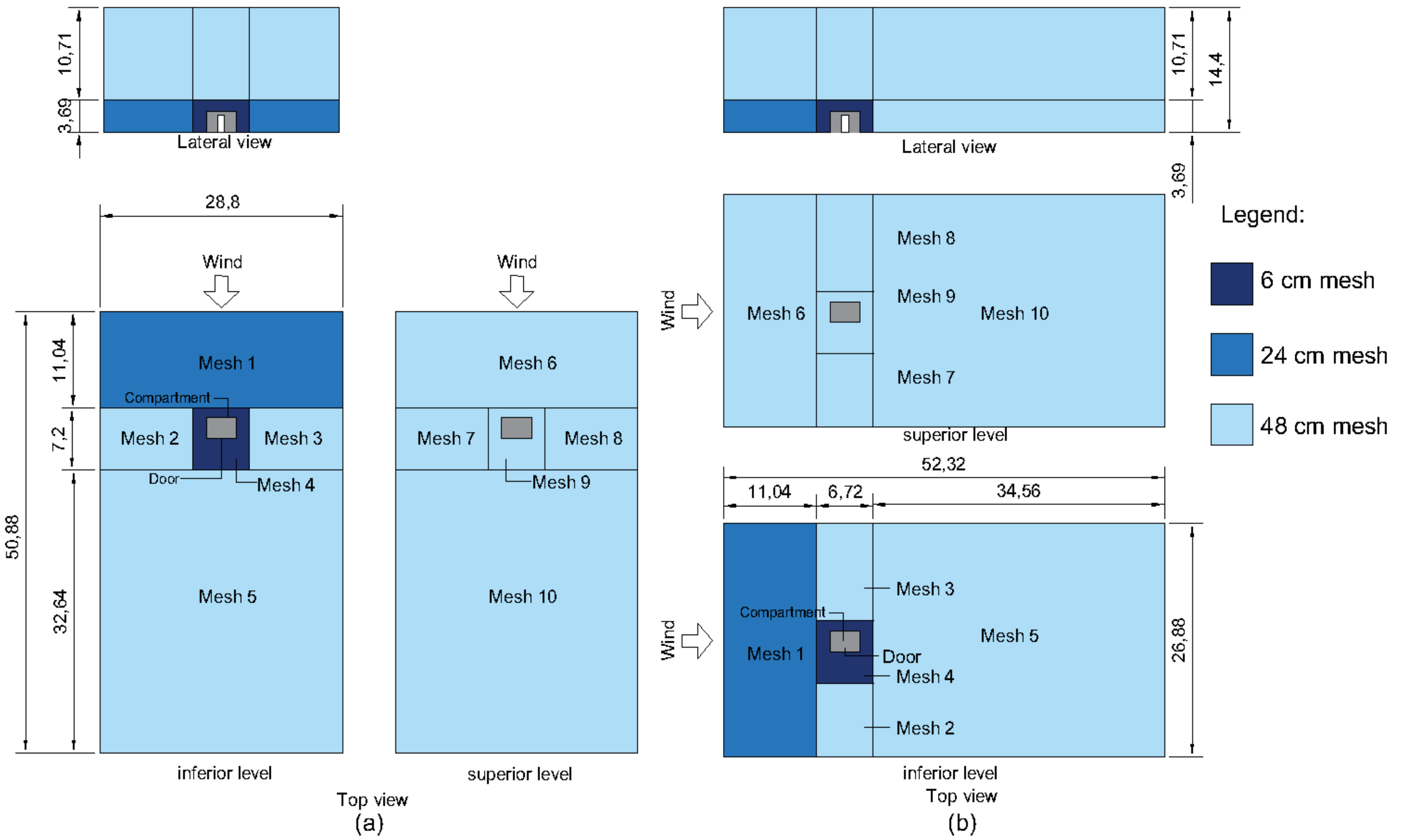


Understanding from experiments - 20 dwellings



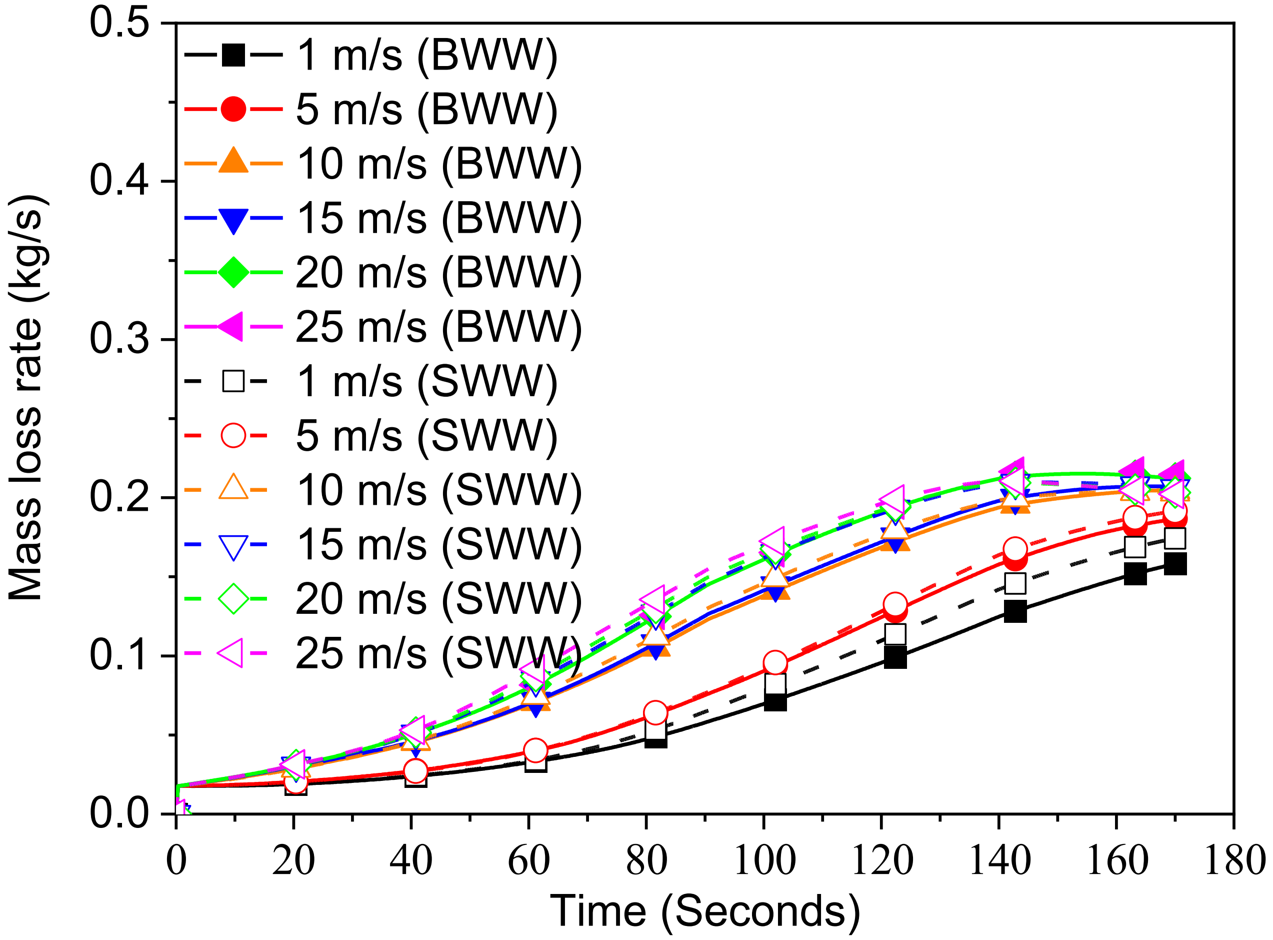
Modelling of single dwelling with wind

- Single opening
- Modelled as thermally thin and thermally thick
- 1m/s --> 25m/s
- Crib model – pyrolysis



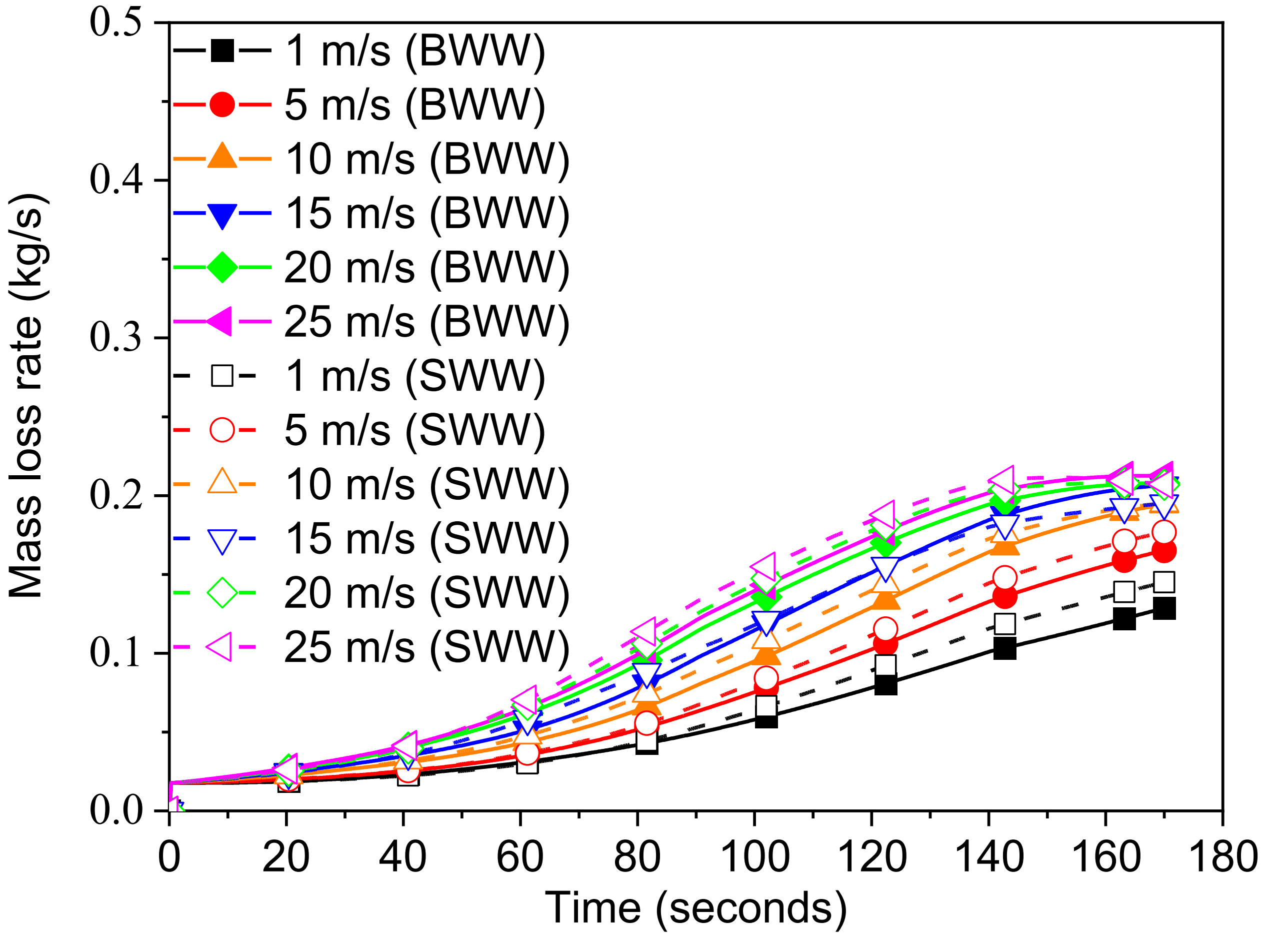
Modelling of single dwelling with wind

- Thin



[a]

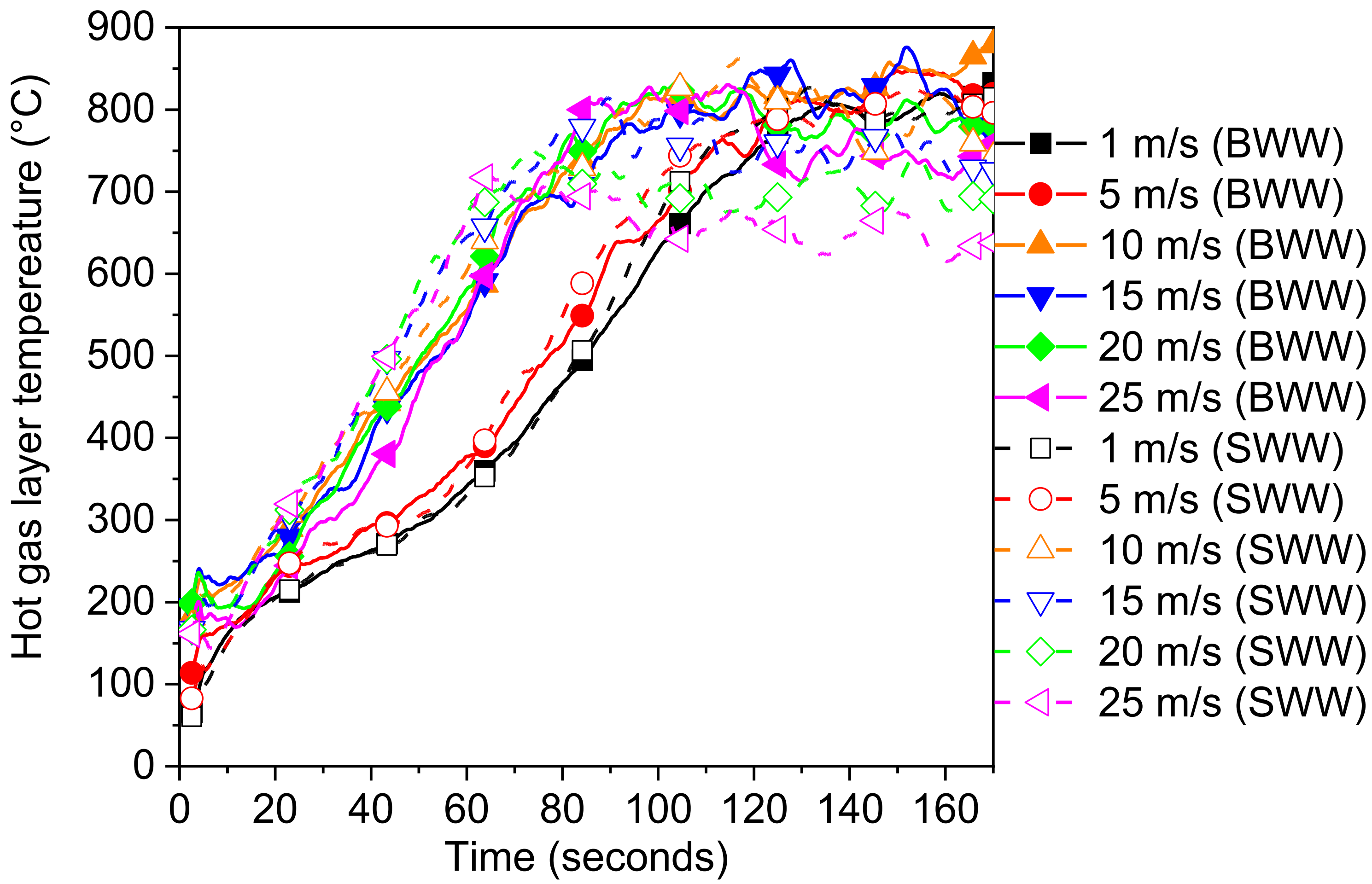
- Thick



[b]

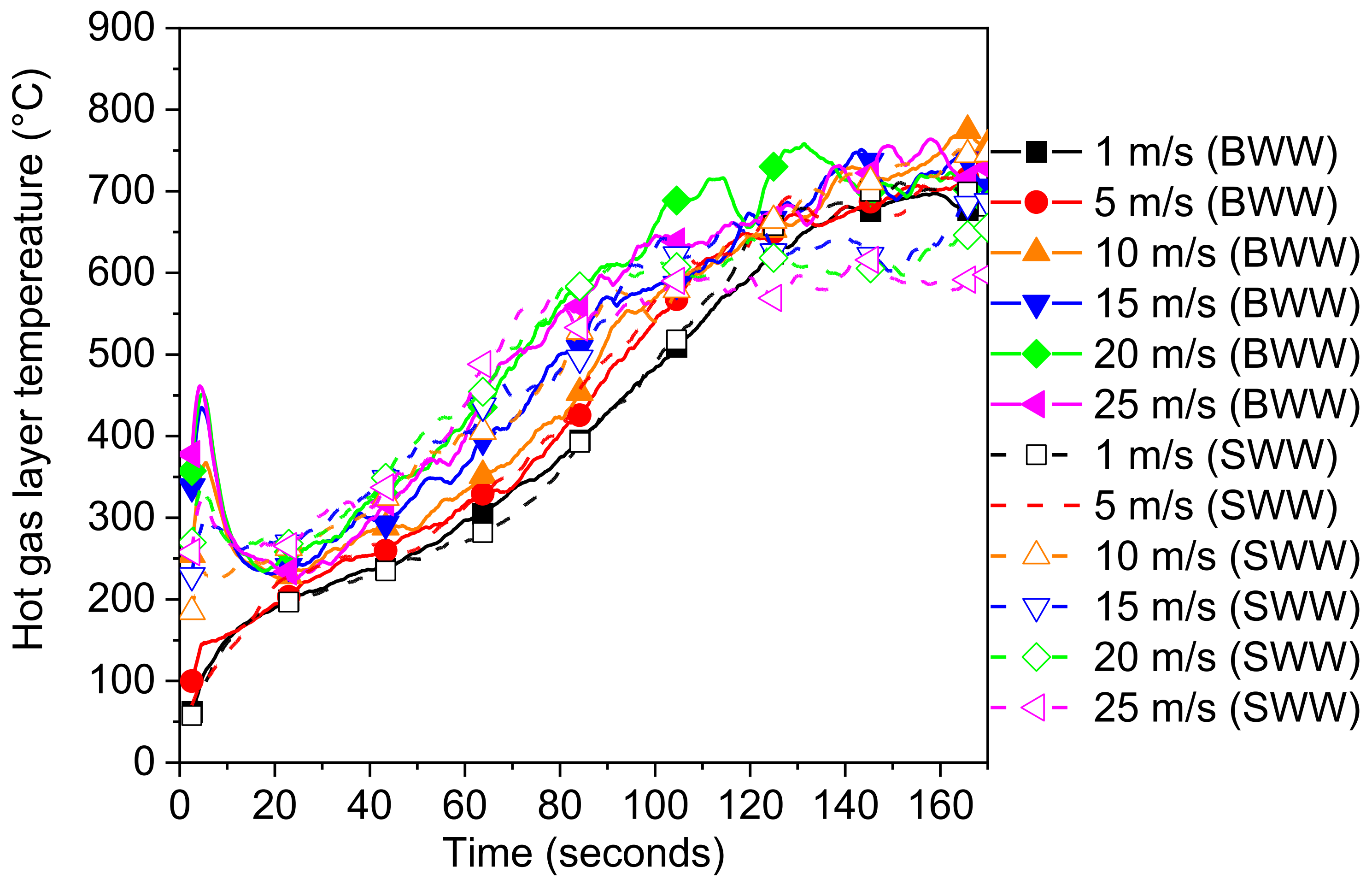
Modelling of single dwelling with wind

- Thin



[a]

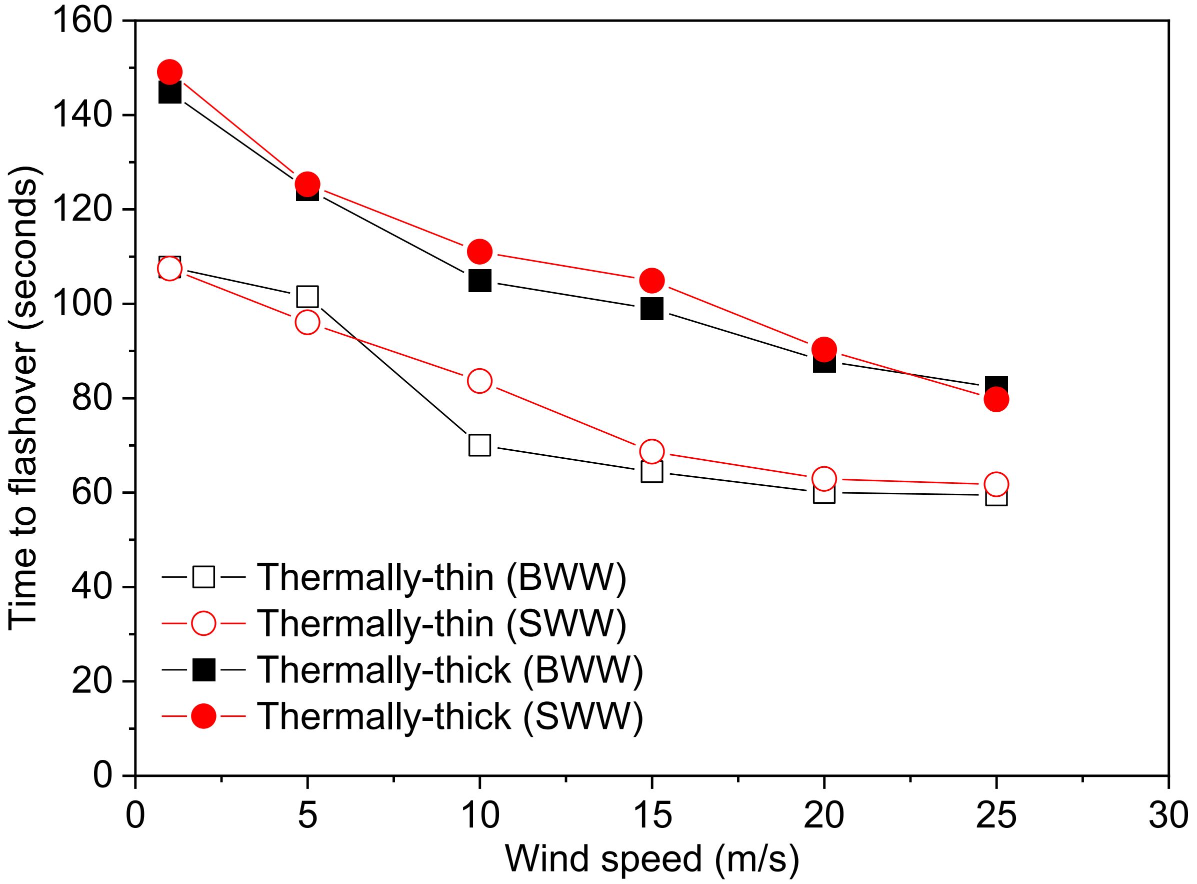
- Thick



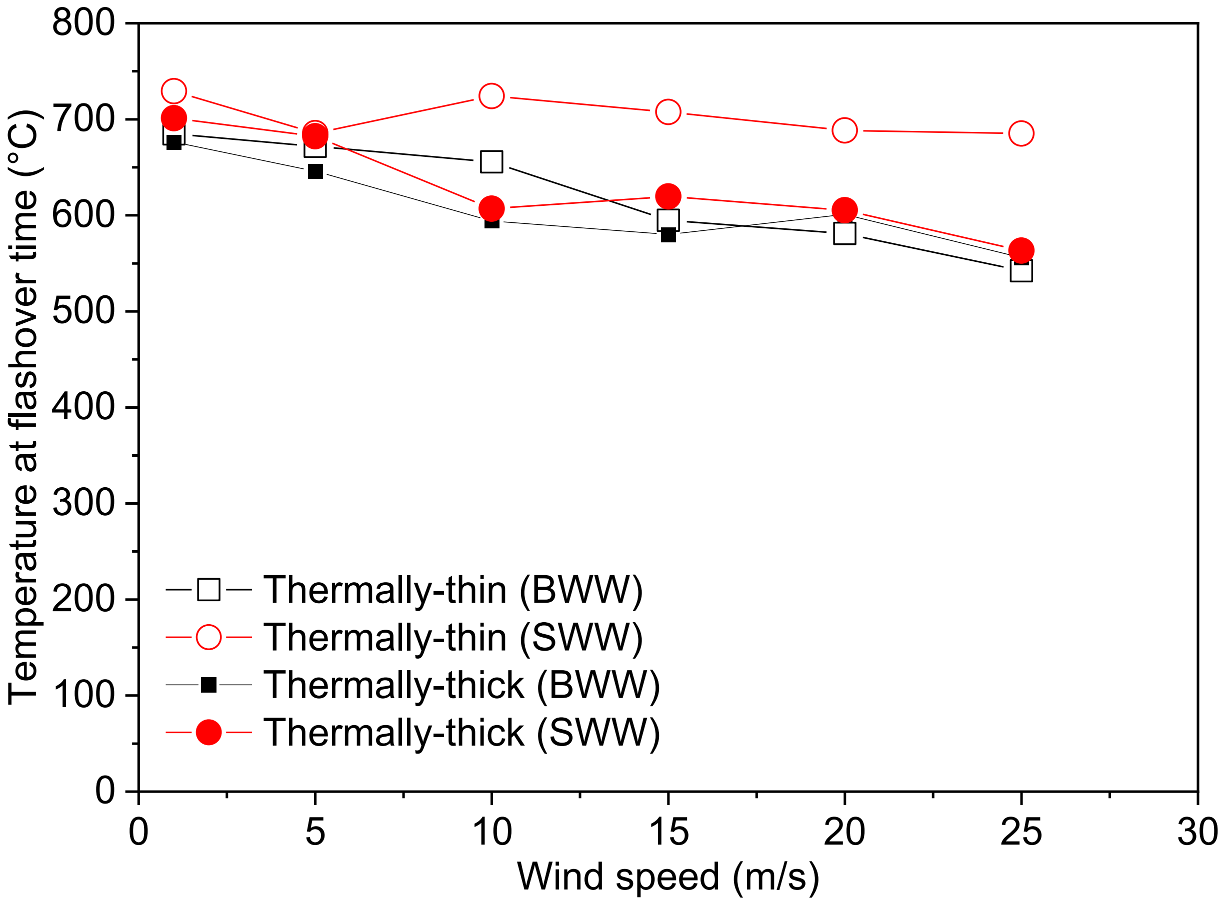
[b]

Modelling of single dwelling with wind

- Time to FO
- Temp at FO



[a]



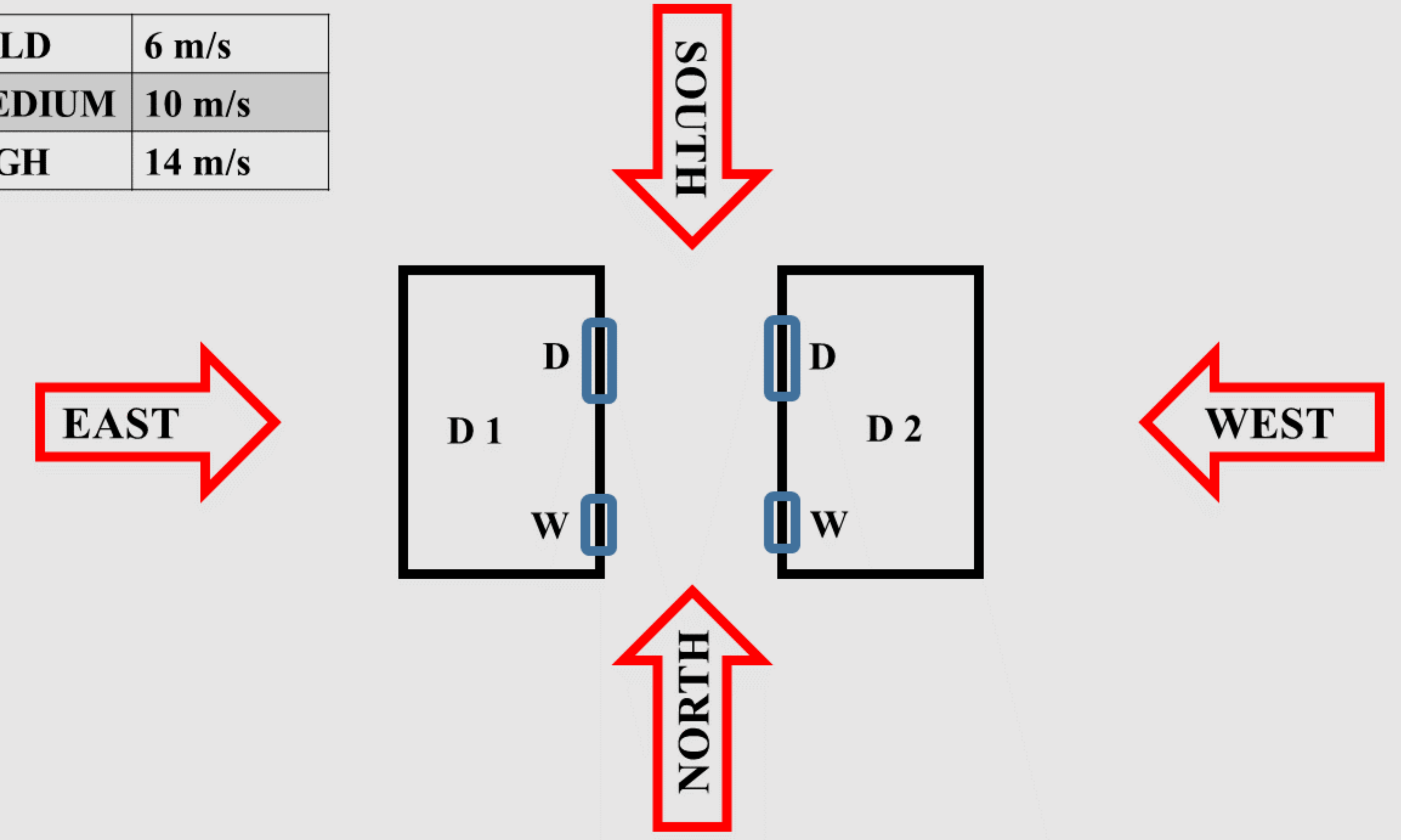
[b]

NB: Definition of flashover is flux at floor level not external flaming

Modelling of two dwellings with wind

- Dwelling 1 (D1) ignited
- Spread to D2
- Two openings

MILD	6 m/s
MEDIUM	10 m/s
HIGH	14 m/s

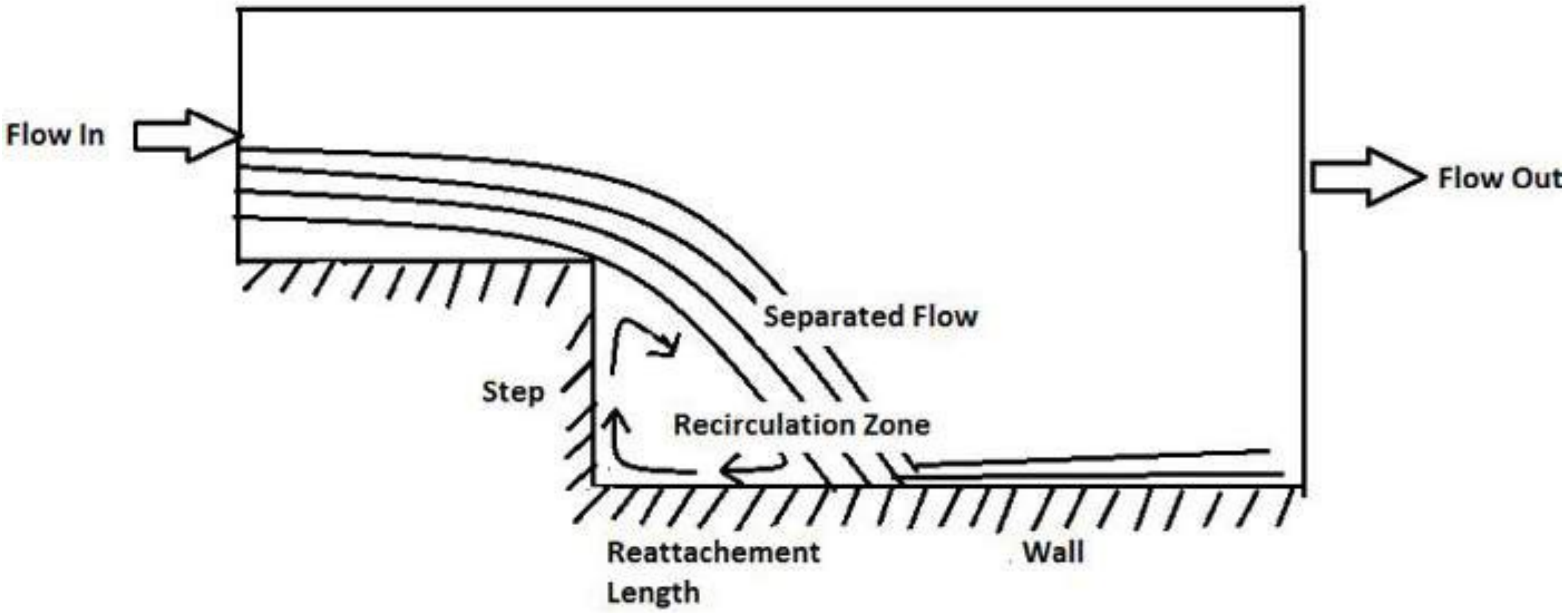


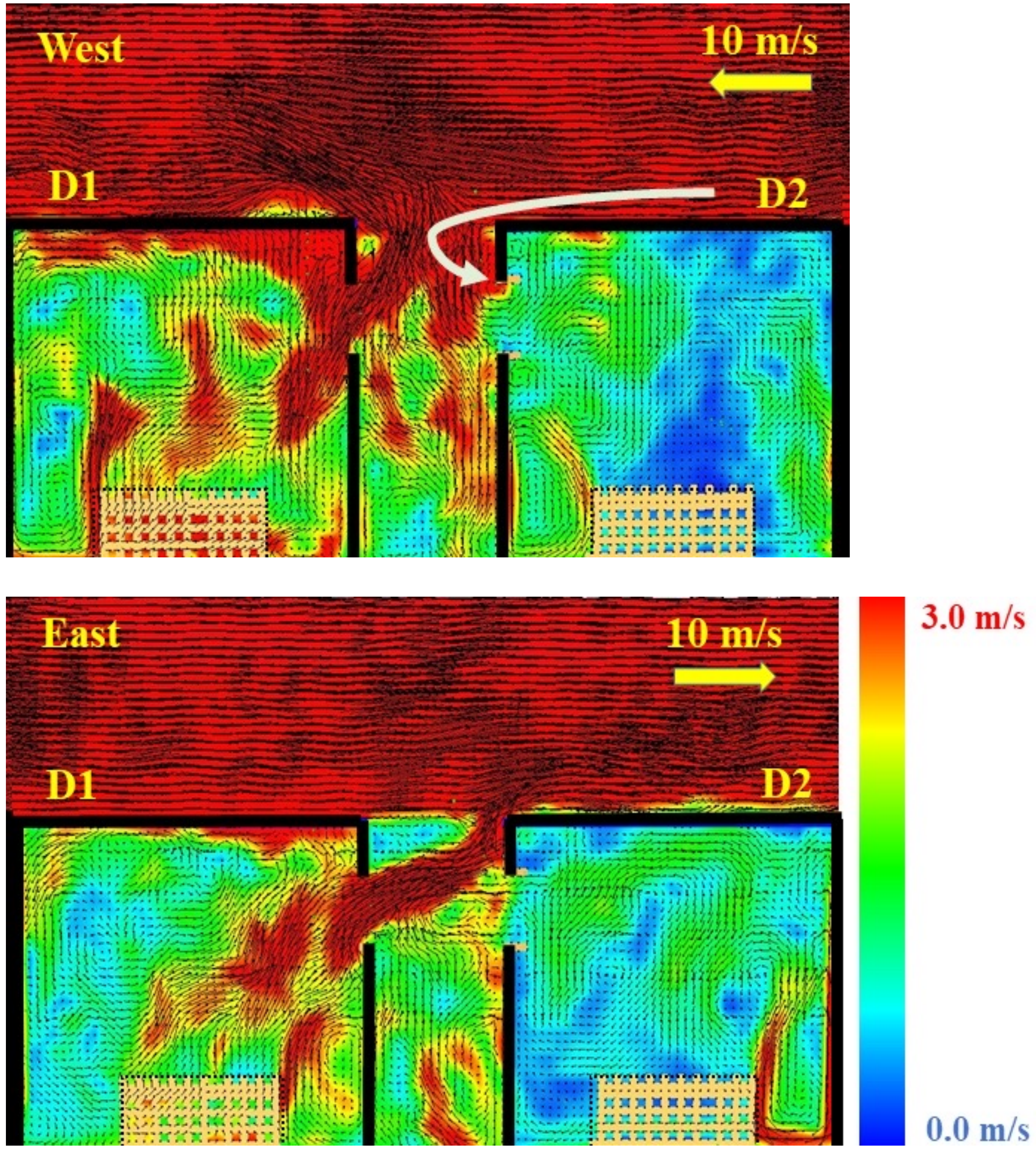
Results

Case	DD	6E	6S	6W	6N	10E	10S	10W	10N	14E	14S	14W	14N
t_{ig} (sec)	28	32	48	32	78	24	58	22	115	46	60	38	128
E_{net} (kW)	-484	-291	-61	-128	-10	-276	-47	-163	0	-452	-17	-166	5
t_{fo} (sec)	326	248	290	316	362	198	354	226	-	112	358	140	-

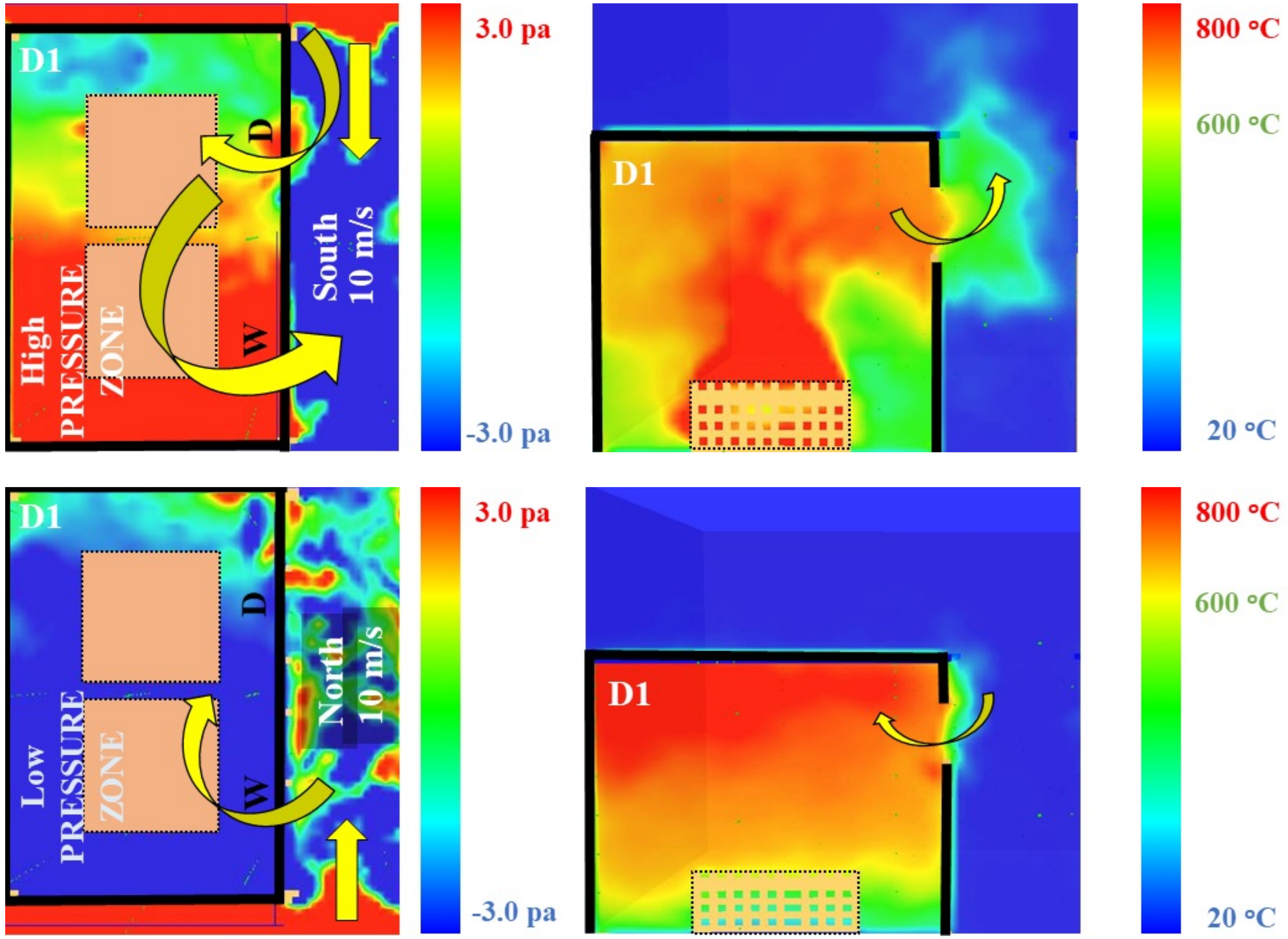
Ignition time of D2, Energy from D1 to D2 (negative it D1to D2), time to Flashover
Why faster flashover in contraflow?
Why is North wind stopping energy transfer

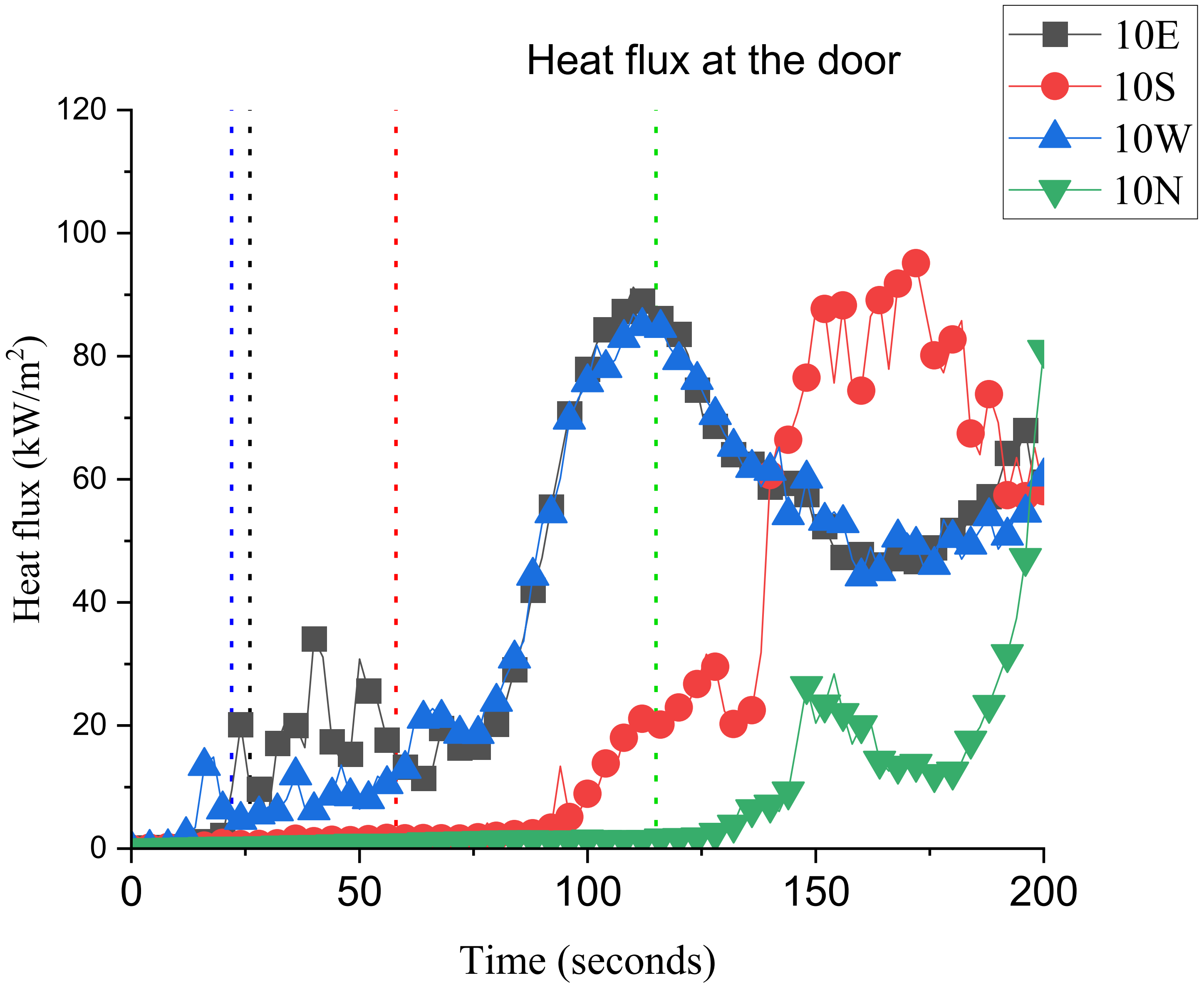
Flow field impacts





Flow field impacts

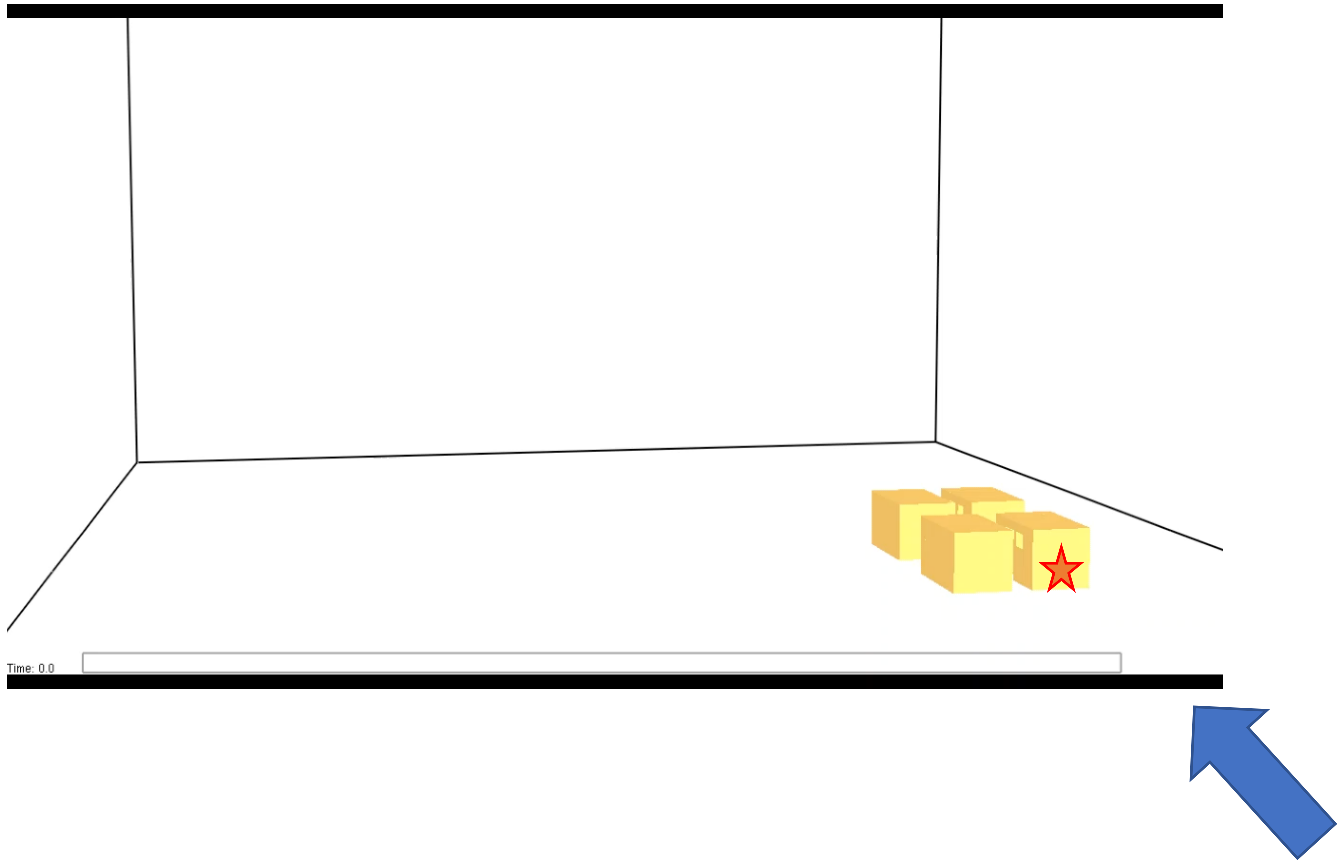




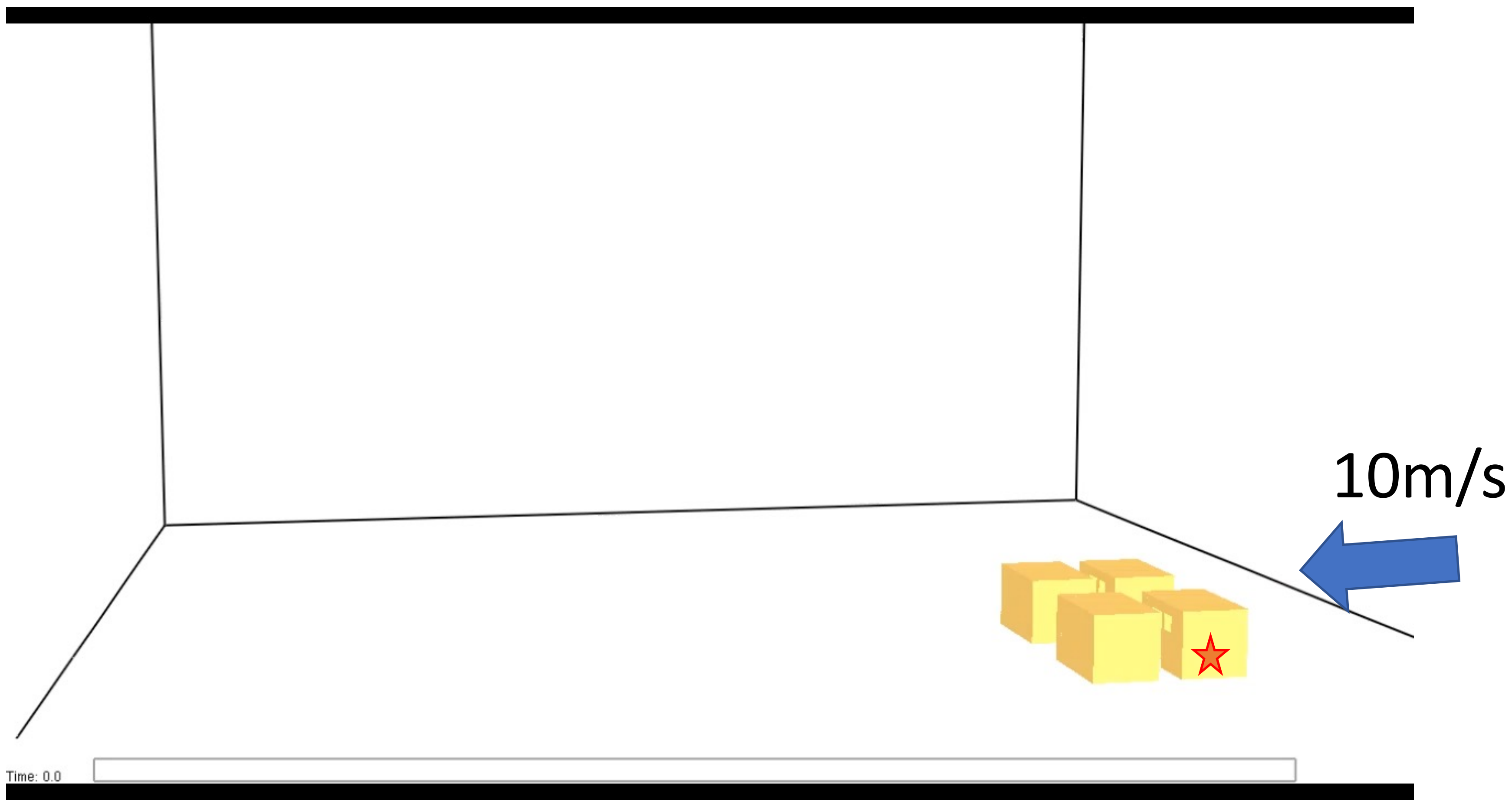
CFD of informal settlements?

12cm mesh in and around structures

Doubling as you get further away to 96cm farthest from structures



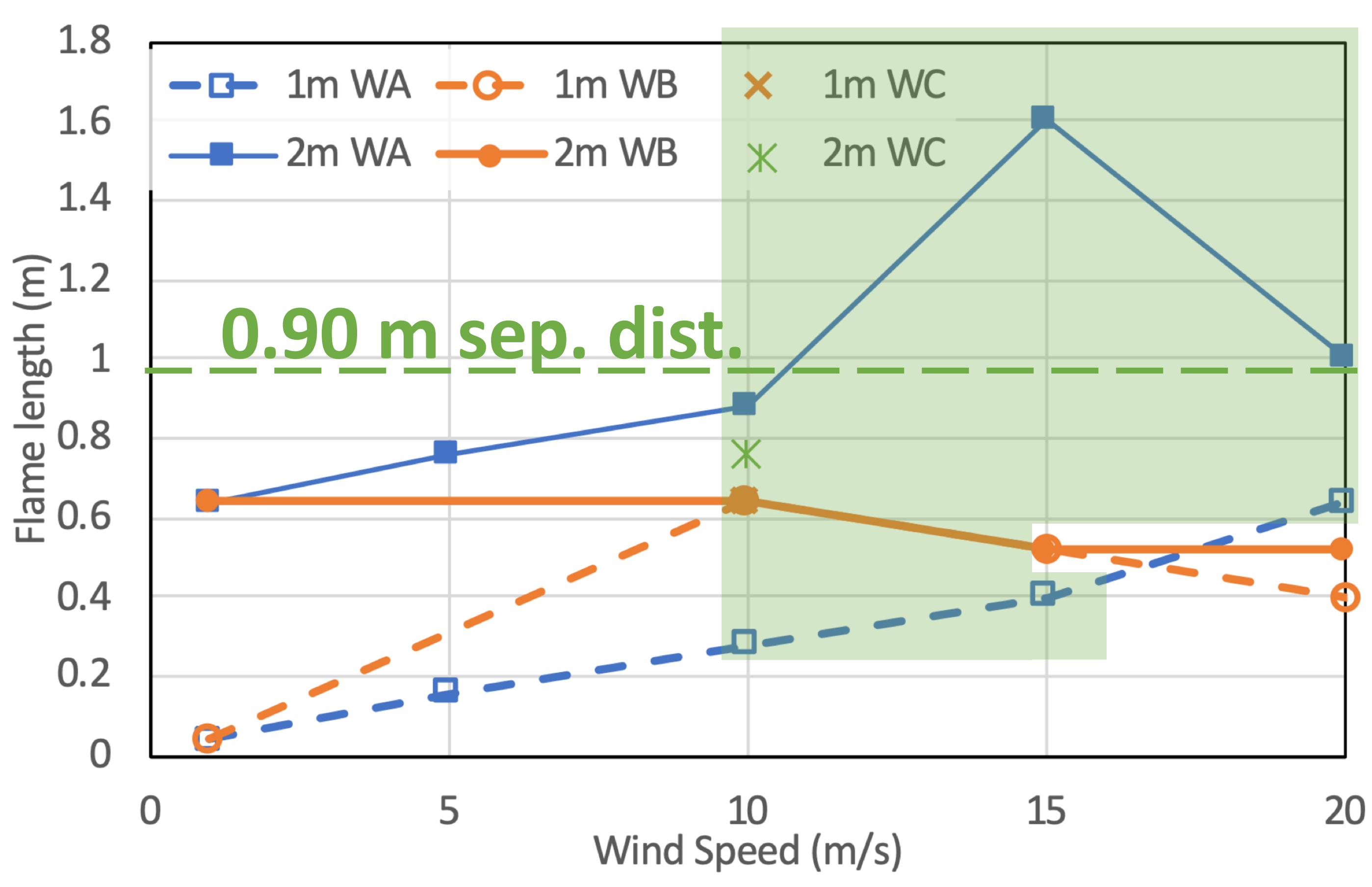
10m/s

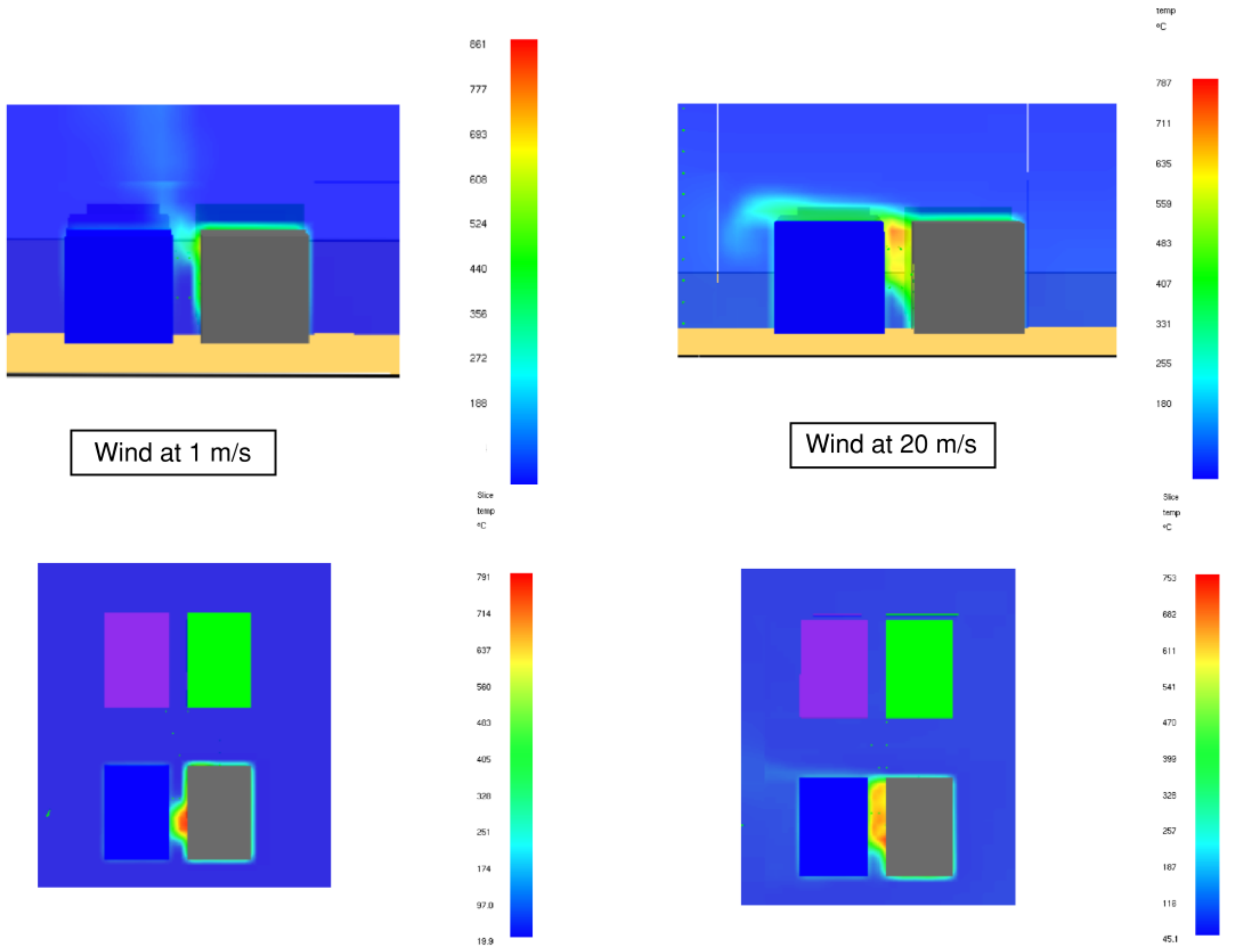


Burners – not modelling pyrolysis

10 processors – 50-60 hrs each

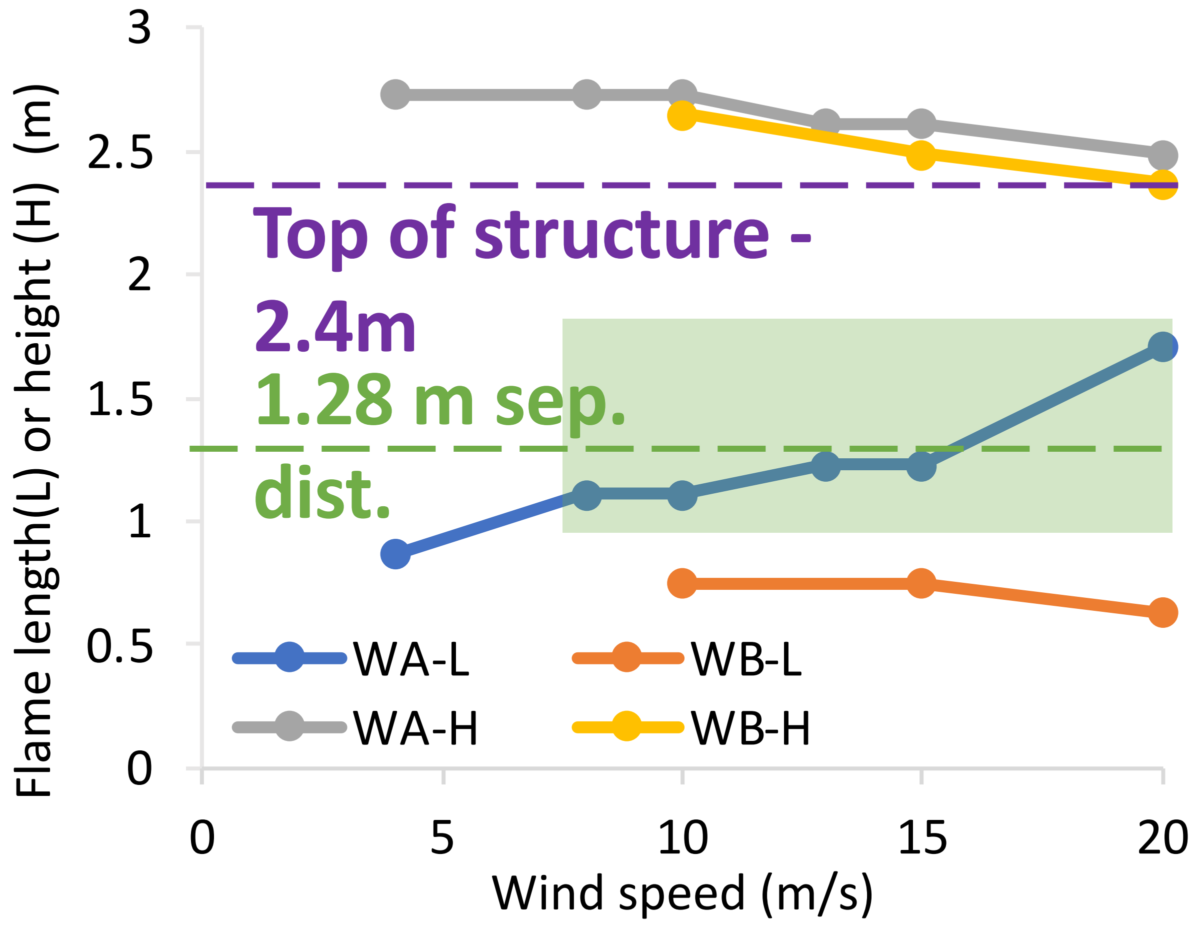
4DW scenarios

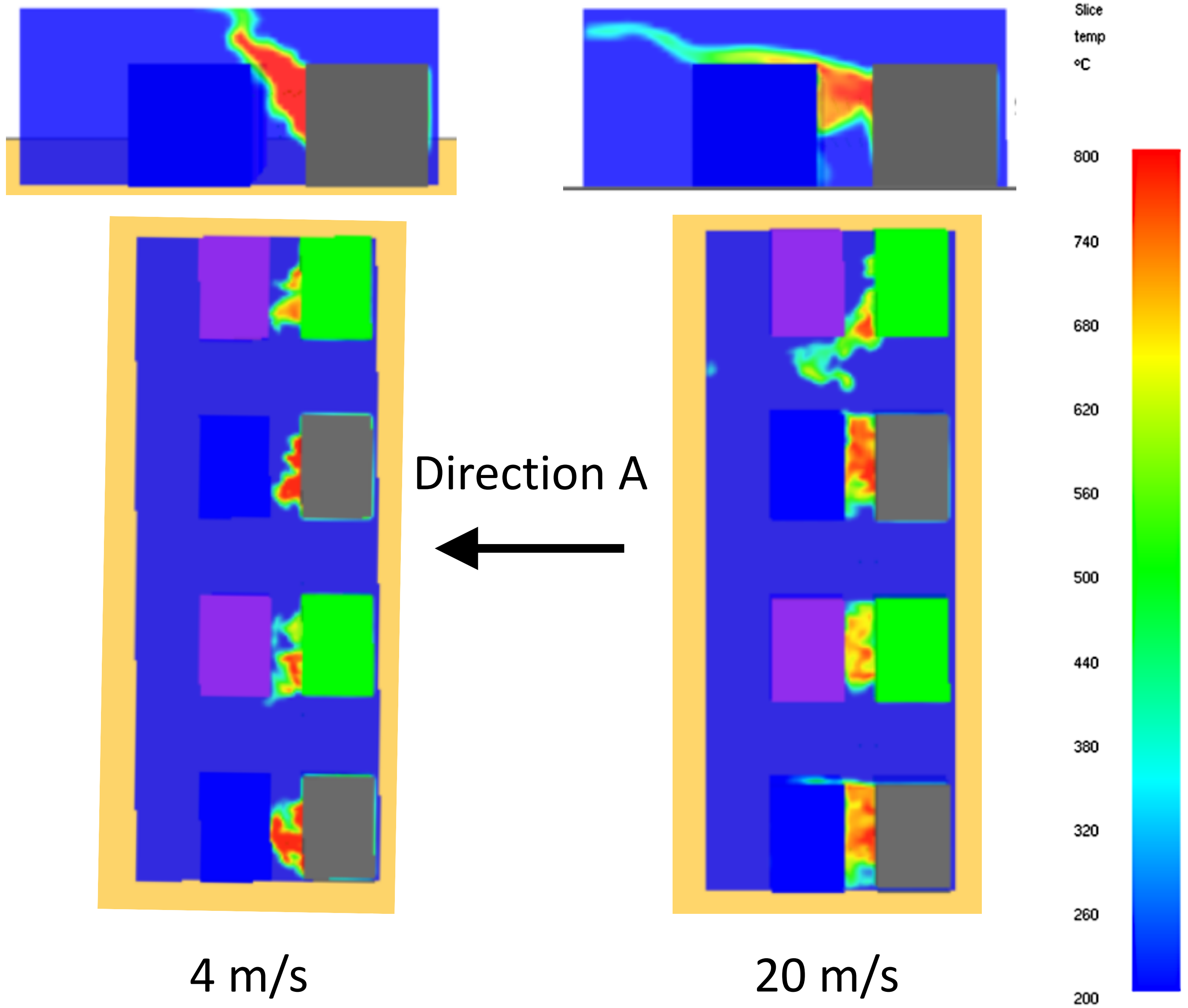




NB: Measurements taken between 200-250 secs "steady state"

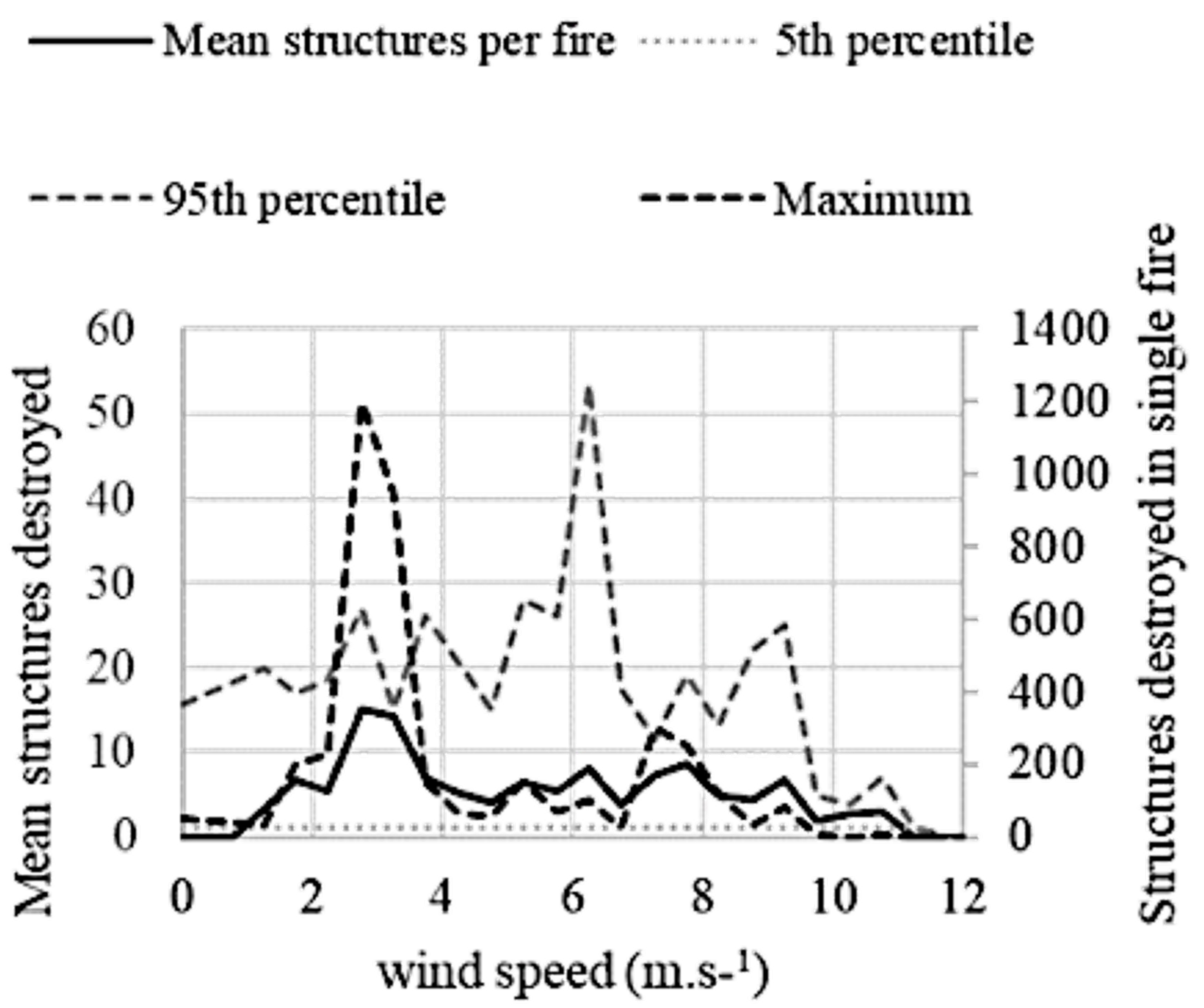
8DW scenarios





Summary of wind influence

- Wind changes everything (but it it not linear)
  - Increases air into compartment
    - Can increase oxygen to fuel
    - Can cool combustion
  - Changes pressure environment in and around compartment
    - Where and how big external flaming is
  - External flames
    - Tilted in 3D depending on wind direction and turbulence around structure
    - Convective cooling also present

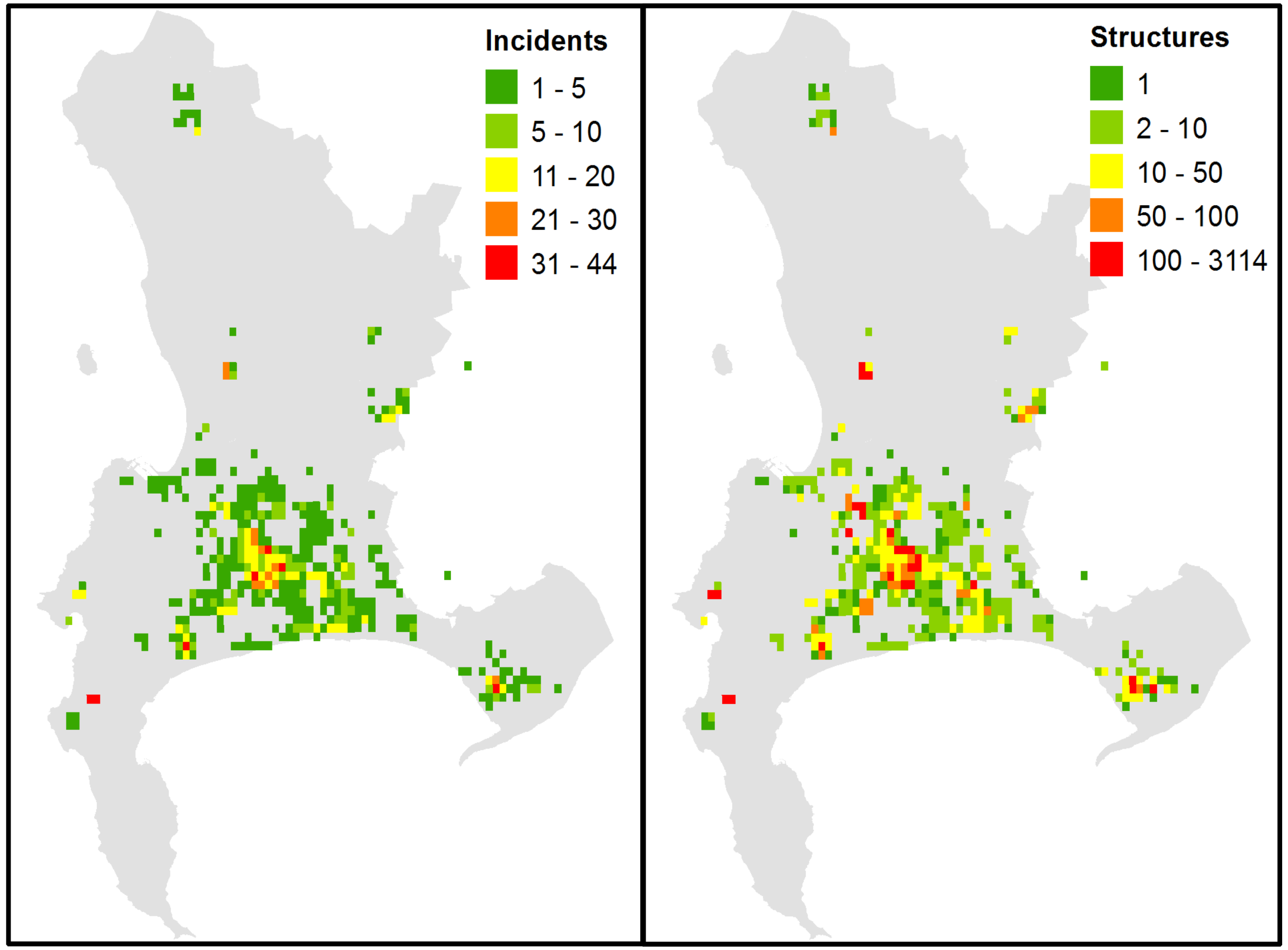


How we are modelling informal settlement fire risk

- **All Models Are Wrong…**

  …Some models are useful

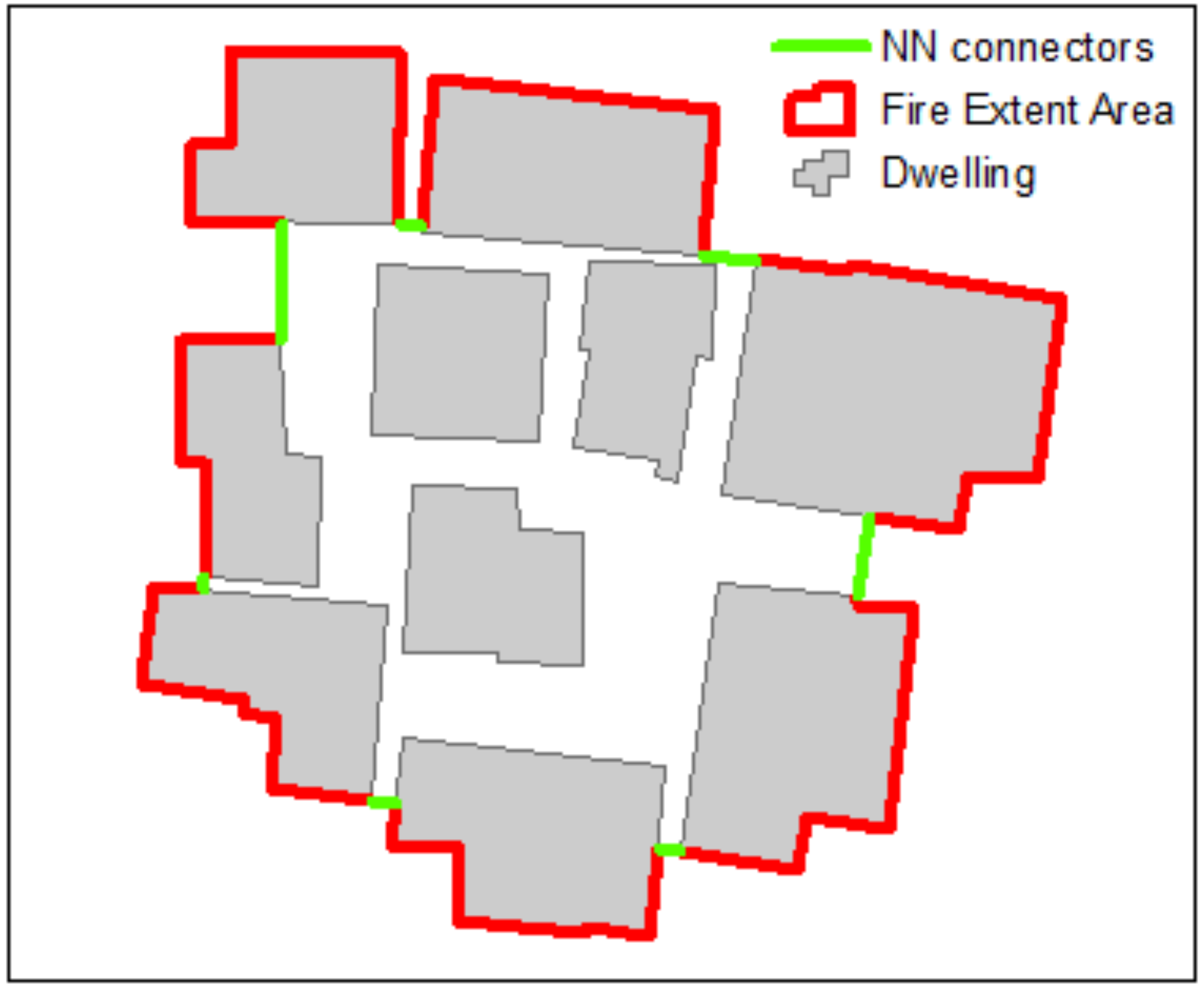
- Statistically
- Spatially
- CFD (e.g., FDS)
- Semi-probabilistic Urban Fire spread models



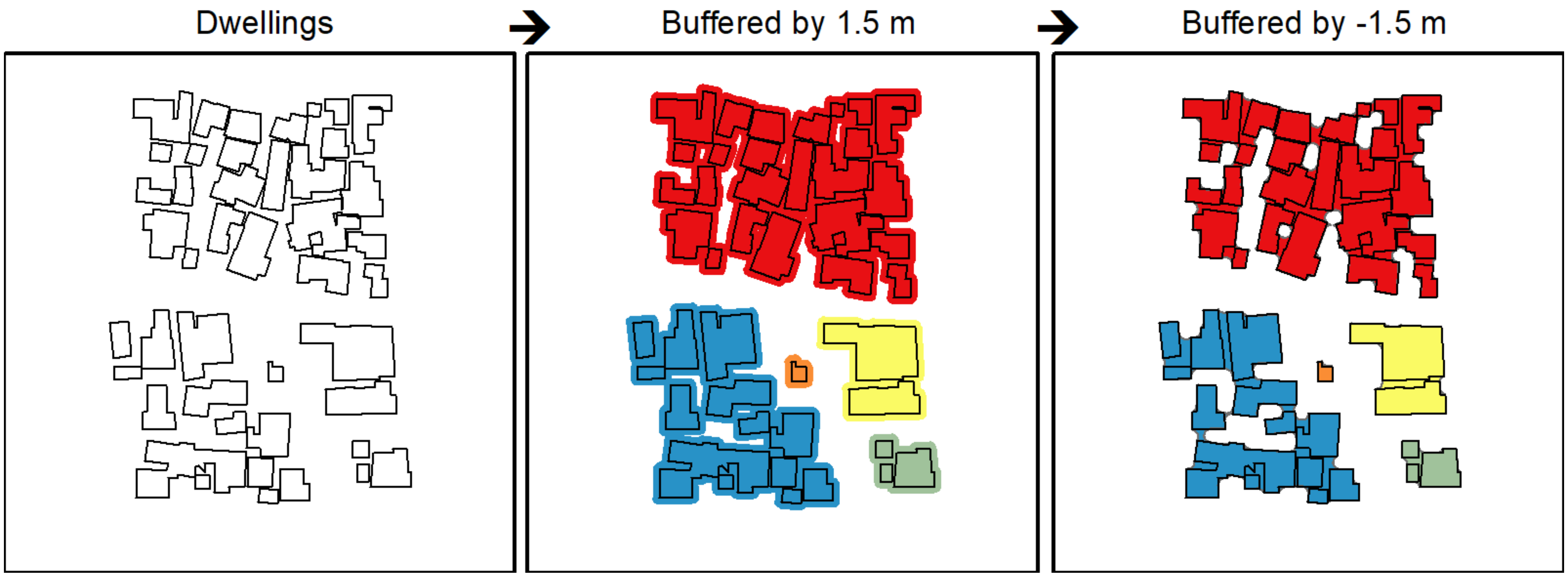
Spatial modelling of risk

- Uses only building footprint data – can determine the relative risk of fire spread.
- Two methods

1. UoA – potential fire area
2. UoA – being a building footprint

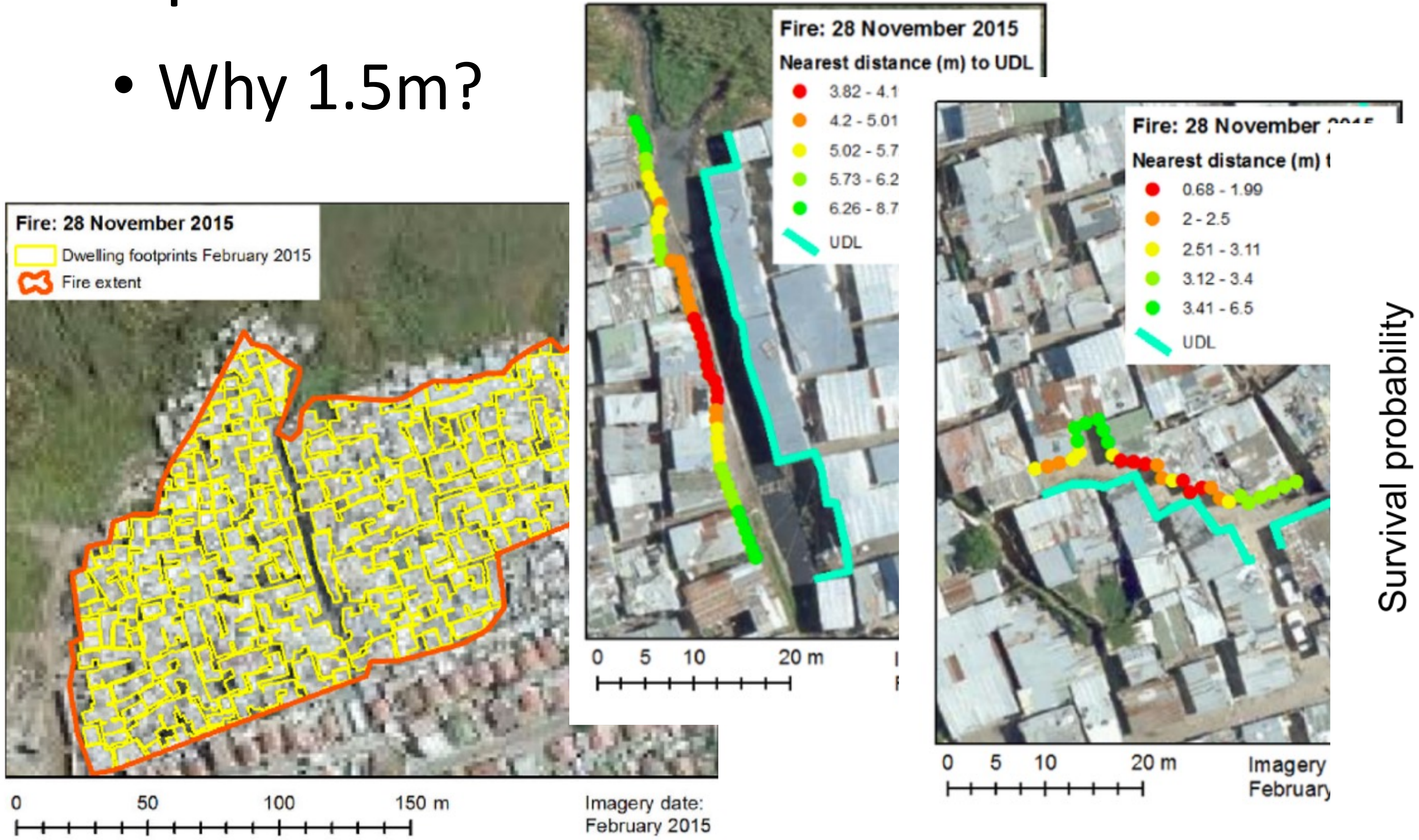


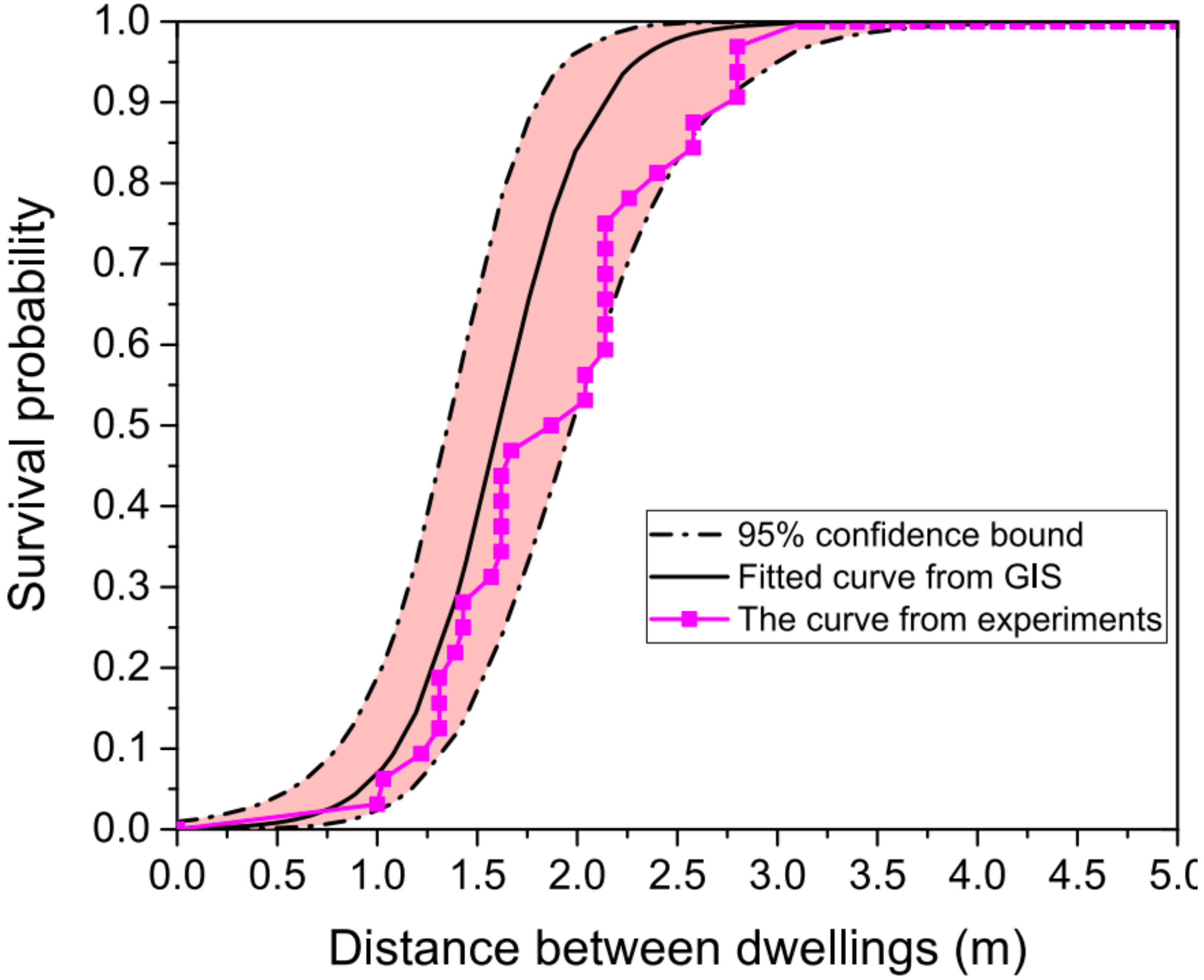
Spatial modelling of risk - PFA



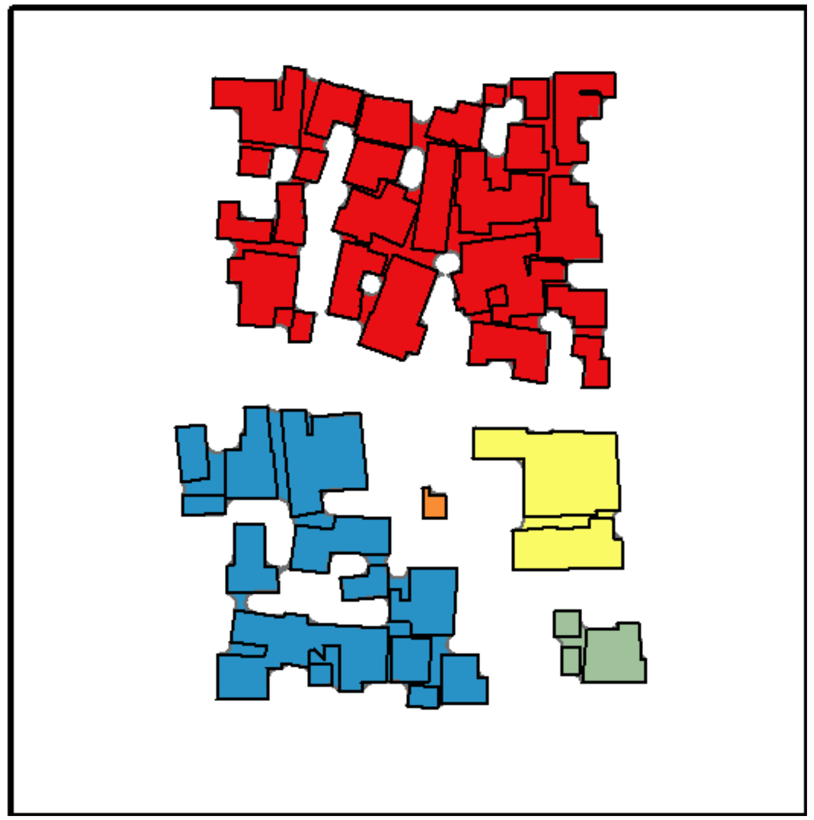
Spatial modelling of risk - PFA

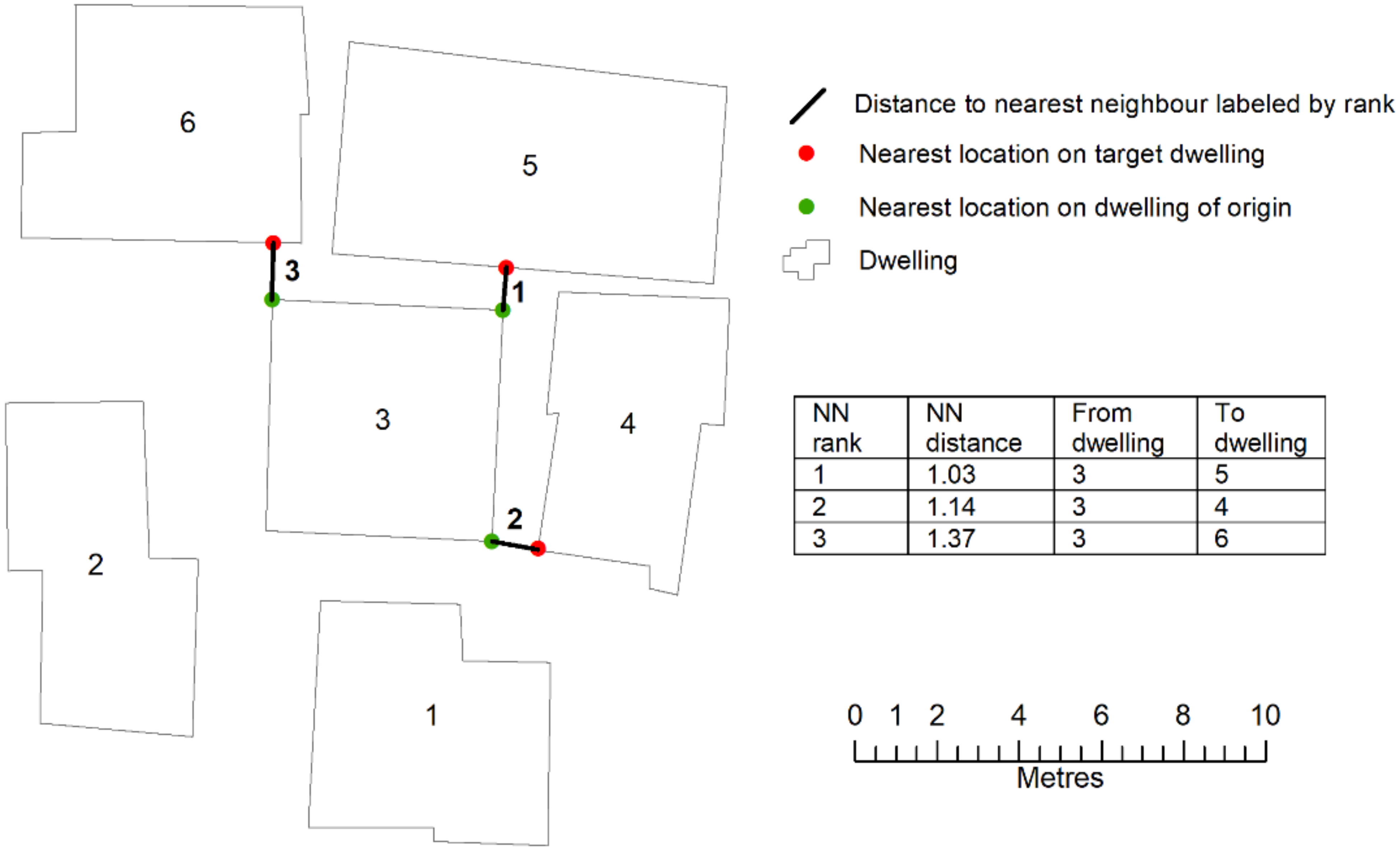
- Why 1.5m?





Spatial modelling of risk - PFA

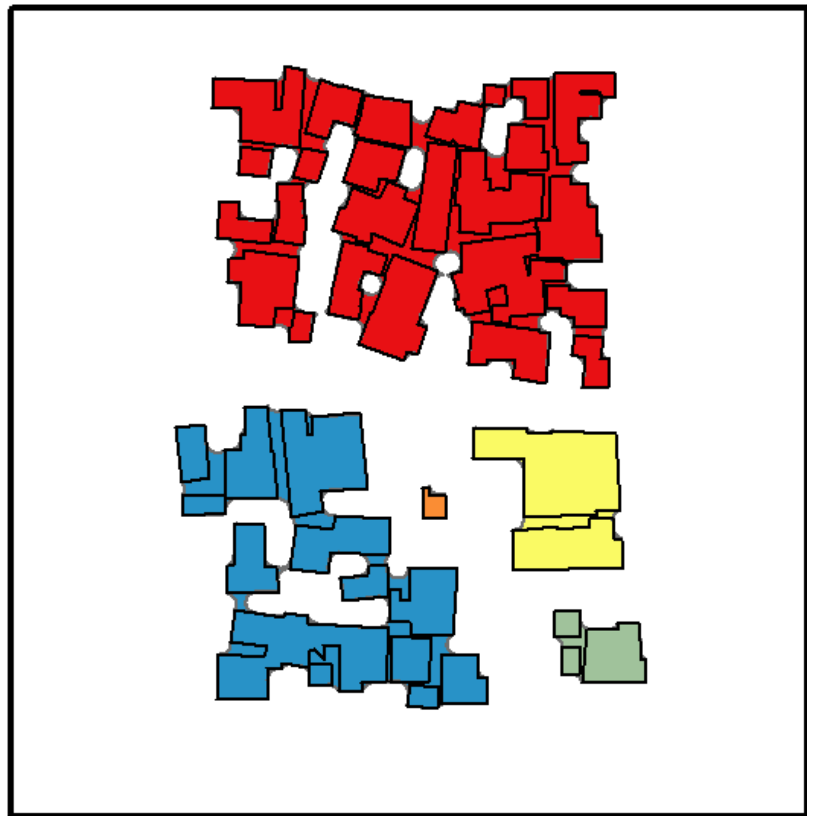




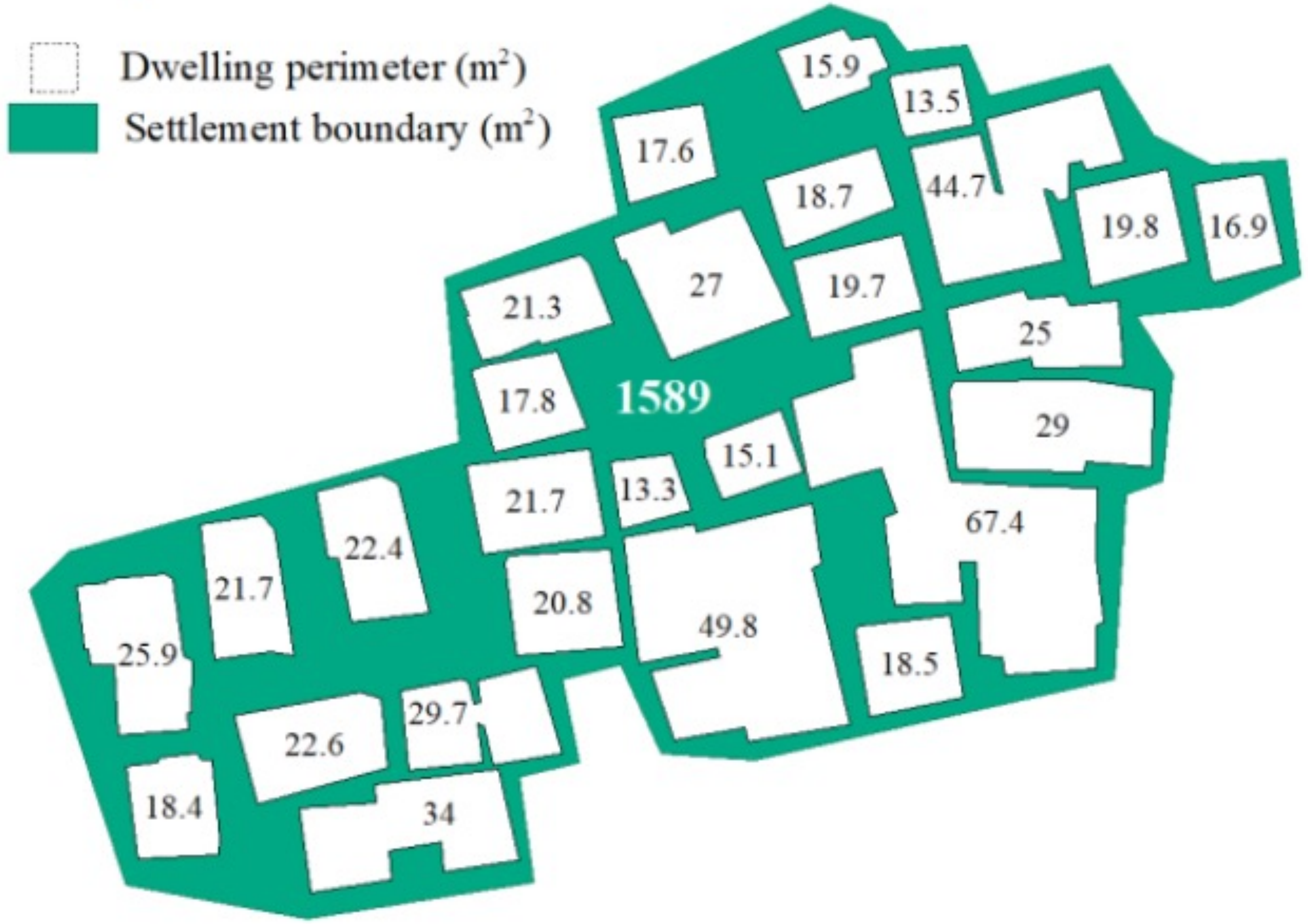
NN rank	NN distance	From dwelling	To dwelling
1	1.03	3	5
2	1.14	3	4
3	1.37	3	6

Euclidean Nearest Neighbour

Spatial modelling of risk - PFA



a) Edge density (ED) = sum of all dwelling perimeters divided by the settlement area
Example = 668.2/1589 * 10000 = 4205 m/m²

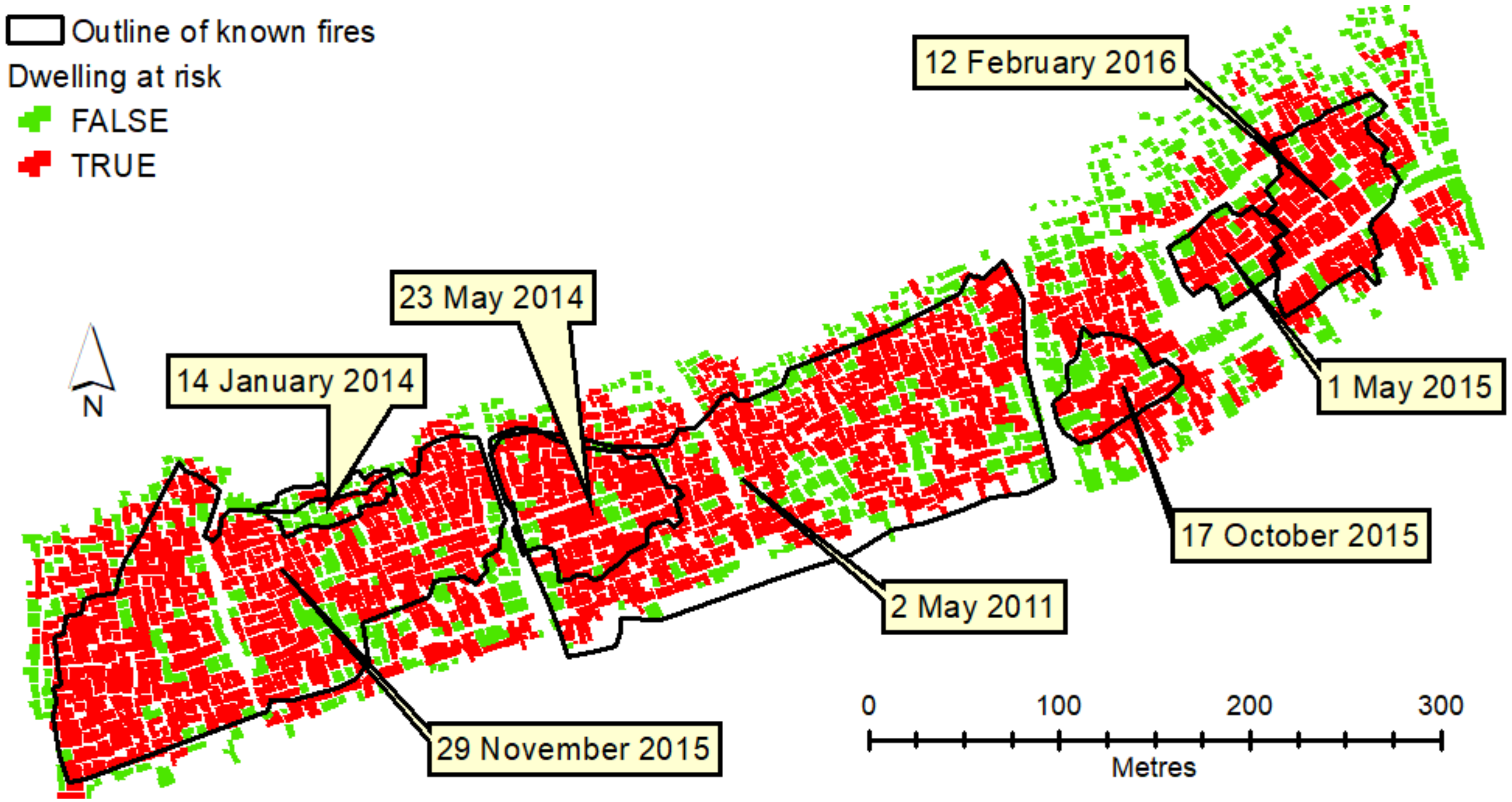


Edge Density

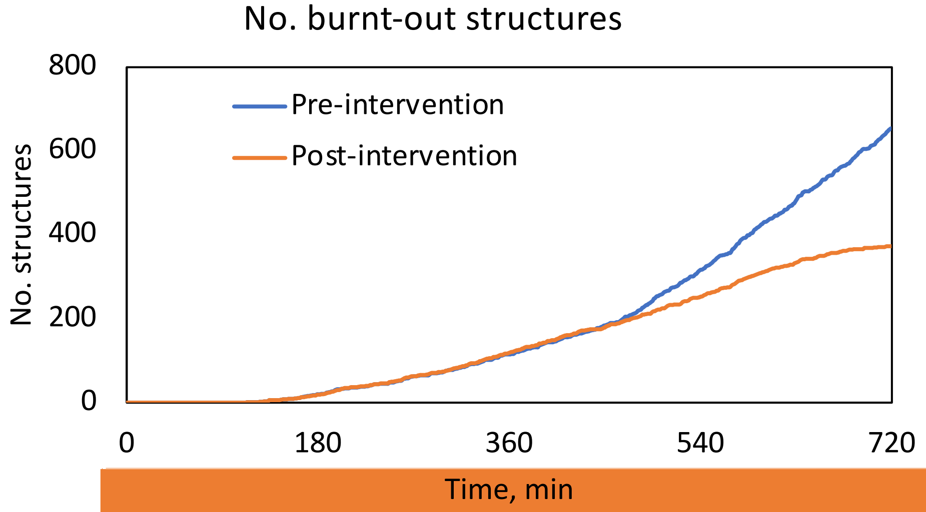
Boolean thresholding

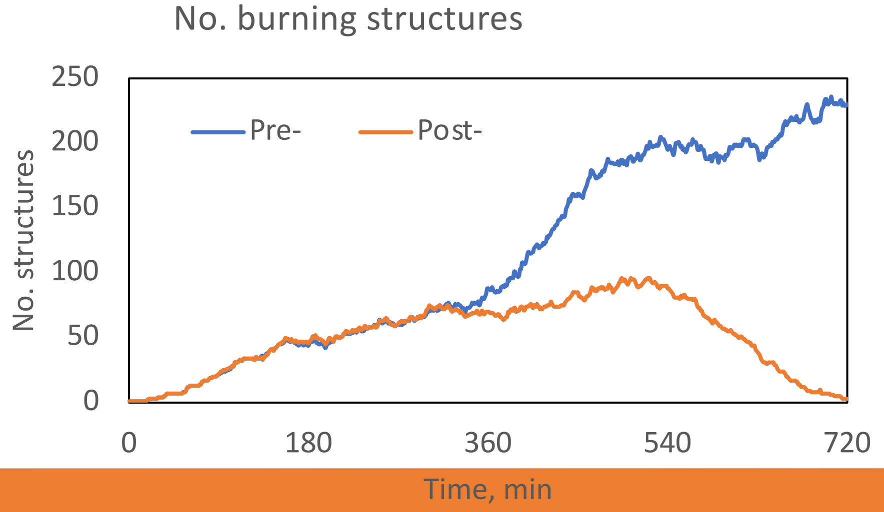
- Increasing the # of NN analysed
  - Lower average ENN_1 and SD of ENN_1
  - Intermediate ED range
  - ENN_{1+3} Range

- Indicate higher fire spread risk*



Urban fire spread models





- Assumes no community or fire service suppression attempts.
- No wind in model above

Urban fire spread models

Example MC simulations 2 second timestep, 8 hour fire duration 100 sims in about an hour

Pre Intervention – 100 random fire locations	
Max no. of times structure was affected:	32
Mean fire size (no. of structures):	325
Max. fire size (no. of structures):	621

Post Intervention – 100 random fire locations	
Max no. of times structure was affected:	18
Mean fire size (no. of structures):	166
Max. fire size (no. of structures):	385

Conclusions

- Urban fire spread is dependent on compartment fire dynamics
  - Boundary conditions of compartment vitally important
  - Different magnitudes of response between thermally thin and thick compartments
- Spread predominantly a mix of radiation and flame contact
- Wind affects BOTH internal and external fire dynamics
- Tools are continually being developed to understand urban fire spread in a variety of contexts
  - CHECK THE ASSUMPTIONS

Conclusions

- What I've not gone through
  - Topography impacts on urban fires
    - slope and the structures themselves – wind shear in urban areas?
  - Atmospheric conditions that promote urban fires (temp/humidity)
  - Other more complex spaces (refugee settlements/mixed material structures)
  - Combustible boundaries of compartments (when do they stop acting like a compartment?)
  - Multi-hazard events (fire following EQ, WUI→Urban transition)
  - Suppression (lack of access to suitable water supplies, people actions to stop spread)

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Beshir Thesis

Google scholar for papers